MULTIMEDIA TRAFFIC MODELING AND BANDWIDTH ALLOCATION IN HOME NETWORKS

By

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by

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To my parents

and to

Bokyung

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IN HOME NETWORKS

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With the dramatic growth of the Internet and new technologies emerging for digital communication within the home, the demand for home networking has increased dramatically. In this research we surveyed several home networking technologies and did a detailed study of HomePlug 1.0 powerline communication protocol. This work gives a comprehensive description of the HomePlug 1.0 protocol, providing analytical, simulation and measured performance results; with comparisons to similar results for IEEE 802.11a/b networking.

Multimedia applications such as digital video and gaming, have become a major driving force for home networking and there has been increased interest in efficiently transmitting multimedia files with QoS guarantees. However, many emerging multimedia applications consume significant bandwidth and the bandwidth is bursty in nature due to the frame structure of the underlying encoding schemes and the natural variations of video scene changes. Having demonstrated that the powerline channel using HomePlug 1.0 and its successor HomePlug AV is an appropriate candidate channel for high speed in-home networking. We then conducted a detailed study of the traffic characteristics of MPEG video in the popular DVD format.

We proposed a model for MPEG-2 video traffic that allows synthesis of DVD traffic. The DVD traffic models are needed to develop new protocols and applications, because the success of network simulation and application design depends on the accuracy of the traffic model. Our model uses two gamma functions to model the cumulative distribution function of frame size which yields a better fit for the observed data than do previous models. This technique, frame-size modeling, was developed by first considering the performance of a single gamma function model as suggested by existing literature. A two gamma function model, using a histogram approach to adjust the gamma function parameters, was shown to produce far superior results.

The final contribution of this research was the development of a novel bandwidth-allocation scheme for multimedia traffic. This scheme uses transmit buffer occupancy to allocate the bandwidth efficiently. It does not need advanced knowledge of frame size, but rather monitors the dynamically changing average transmitter buffer size and average allocated bandwidth. According to these values, the proposed scheme increases or decreases the bandwidth allocation at regular intervals in conjunction with a smoothing algorithm. This algorithm is designed to reduce the assigned bandwidth and the variation of assigned bandwidth. Extensive simulation results show that the proposed bandwidth reservation scheme outperforms the best previously known schemes, with an over allocation of less than 10%.

CHAPTER 1
INTRODUCTION

These days, many homes have more than one computer, and people want to implement a home network system. Home networking allows the sharing various formats of data among various devices within the home. There are several technologies for home networking, but most people are unaware of how they work and what technology is suitable for their environments.

1.1 Home Networking

The main considerations for home networking are ease of installation, low cost, and more than 10 Mbps throughput with reliable connection. Several home networking options meet these criteria.

Phone-line networking (HomePNA) uses the existing phone line infrastructure. HomePNA 2.0 supports speeds up to 10 Mbps. HomePNA suffers from impulse line noise, cross-talk, attenuation. In addition, the number of phone jacks is limited in typical homes. Another option is to install a ethernet network. Ethernet is fast, reliable, and widely used; but new wire installation is required. Wireless networking is one of the most popular home networking solutions. Some of the types of wireless networks are Bluetooth, HomeRF, and Wireless LANs. Wireless LAN allows mobility and eliminates new wire installation; but it has limited coverage area and less security, it interferes with cordless phones operates in the same frequency range, and does not provide QoS for multimedia. Powerline Networking uses existing electrical wiring for networking. Powerline networking supports up to 14 Mbps and provides strong security protection. But this data rate is not sufficient to support multiple multimedia stream in home networks. The HomePlug alliance is working on a new technology called HomePlug AV, that is designed specifically to support multimedia. HomePlug AV is designed to support distribution of data and multi-stream entertainment throughout the home, at about 100Mbps. In the first part of this work gives the first comprehensive description [1] of the HomePlug 1.0 protocol, providing a comparison with the 802.11b protocol.

1.2 Multimedia Traffic Modeling

We also proposed a simple MPEG-2 traffic modeling and reservation scheme to aid in the improvement of bandwidth utilization and to reduce transmission delay. Although MPEG frame sizes fluctuate considerably, this scheme smoothes bandwidth allocation.

We need to design and manage network systems that allow us to guarantee prescribed levels of network performance. Thus the VBR video traffic model is presently the subject of considerable research. It would, for example, be useful to have the characteristics of the VBR video traffic by genre. In this regard the behavior of VBR video traffic can be categorized into high action, animation, drama, or sci-fi.

Several different traffic modeling approaches have been developed that are based on a first- or second-order auto-regressive processor, the Markov chain model, and self-similarity [2, 3, 4, 5].

Our modeling scheme in the present work uses a two gamma distribution function model for which the required parameters are empirically determined. We shoed that the combination of two gamma distribution function scheme is better than a single gamma distribution function scheme according to the Mean Square Error(MSE) test, which further combinations of gamma functions do not yield improved result.

1.3 Bandwidth Allocation Scheme

The design of an efficient bandwidth allocation scheme for multimedia traffic is another important issue. An improper bandwidth allocation scheme will result in poor network performance. It could result in unacceptable transmission delay, overflow at the receiver buffer, or poor bandwidth resource utilization.

Several bandwidth smoothing algorithms has been proposed in the past decade. Earlier works relate to reducing the burstiness of bandwidth variations, and they require frame-size information before calculating the transmission schedule to minimize the bandwidth variation [6, 7, 8].

The proposed bandwidth smoothing algorithm developed in the dissertation uses only the current buffer information, and does not need any a-prior frame-size information. Because it does not need to parse the MPEG file to get each frame size in advance, it reduces the

complexity and buffering time at the receiver. With a smoothing algorithm, it maintains the average buffer size and average assigned bandwidth size with minimal over allocation levels much smaller than required by previous methods.

1.4 The Outline of Dissertation

The rest of dissertation is structured as follows. Chapter 2 is an overview of Home networking, reviewing the various home networking technologies. Chapter 3 provides a detailed description of PHY and MAC protocol for powerline home networking. Chapter 4 explains the MPEG standard. Chapter 5 derives the key characteristics of DVD frame size for a variety of genres of movies. Chapter 6 gives a description of two gamma distribution algorithm for MPEG traffic modeling and synthesis. Chapter 7 explains the smoothing bandwidth allocation algorithm and shows the results. Chapter 8 discusses our observations, possible uses of the proposed algorithm, and future extensions of our work.

CHAPTER 2
IN-HOME NETWORKING

With multimedia becoming an integral part of our lives, establishing a reliable home network to support multimedia is of great interest. A home network can be established using various technologies such as phone lines [9], wireless [10], power lines, and Ethernet. In what follows us give a brief description of each of this options for home networking with the latter three being potential successful candidates [11].

2.1 HomePNA

Phone-line networking, most commonly referred to as HomePNA, is based on the specifications developed by the Home Phone Networking Alliance (HPNA). Phone-line networking is also based on the idea of "no new wires". It uses the existing phone line for communication within the home network. It is convenient to use and also inexpensive. A phone line network is installed at most homes and does not need any extra installation or networking equipment. HomePNA 2.0 operates at a rate of up to 10 Mbps, even when the phone is in use, but it is still 10 times slower than fast Ethernet, which operates at 100 Mbps. The latest technology, HomePNA 3.0 is expected to support data rates of up to 128 Mbps.

One main disadvantage is interference with voice traffic after installation of HomePNA. The HomePNA network also needs a phone jack near every unit, and there is a physical limit of 1000 feet of wiring between devices. Residential phone lines are good for carrying voice signals; but they are not well suited for supporting high-speed data. Their attenuation and impedance characteristics are not well controlled. HomePNA 1.0 employs Frequency Division Multiplexing (FDM) and has three channels. The first channel supports ordinary telephone service, the second channel is for carrying ADSL signals to access the internet, and the third channel is for networking of computer data and entertainment applications. HomePNA 2.0 makes use of Frequency Diverse Quadrature Amplitude Modulation (FDQAM), which increases speed and reliability by sending duplicate versions of the signal over the wire. Most

homes do not have adequate wiring to handle HomePNA 2.0's speed. In the United States, 99 % of all homes can run 1 Mbps phone-line networks, while about 80 % can use 10 Mbps models, according to HomePNA research. The different wire configurations and low-quality wires used in older homes may also impede data transfer. HomePNA 1.0, which supports data rates of about 1Mbps is considered very slow for transmitting high-bit-rate applications like DVD video which needs 3-8 Mbps, HDTV (20 Mbps), or MPEG video (4-8 Mbps). HomePNA 2.0 boosts the speed up to 10 Mbps. The third generation HomePNA, HomePNA 3.0, reaches an unprecedented data rate of 128 Mbps, with optional extensions reaching up to 240 Mbps. HomePNA 3.0 products are expected to hit the market in the last quarter of 2004.

2.2 Ethernet

Ethernet is the most popular networking standard used today. It is versatile, in the sense that the equipment needed for an Ethernet-based network can be as simple as two network interface cards (NIC) and a cable, or as complex as multiple routers, bridges, and hubs. This flexibility makes it useful in all fields. Ethernet is by far the fastest networking technology working at data rates up more than 100 Mbps. It uses the IEEE 802.3 networking standards. It is extremely reliable and easy to maintain, once set up. The number of devices that could be connected on the Ethernet network is also unlimited. The disadvantage is that first-time set-up and configuration can be difficult and expensive. Additional equipment is also required if there are more than two computers. Carrier Sense Multiple Access with Collision Detection (CSMA/CD) is the protocol used in the Ethernet to regulate communication among nodes and as given there is not guaranteed Quality of Service as required by multimedia networking.

2.3 Wireless Technology

Wireless networking is another way in which a Home Network can be established. In this kind of connectivity, no wires are used. Communication between devices is carried out using RF (Radio Frequency) signals. Some of the types of wireless networks are Bluetooth, IrDA, HomeRF, and Wireless LAN.

Bluetooth was established by Ericsson, IBM, Intel, Nokia and Toshiba in 1998 to provide an inexpensive and low-power wireless interface. The original purpose of this standard was to

support digital voice and data among mobile devices. It communicates at a frequency of 2.45 gigahertz. It uses a technique called Frequency Hopping Spread Spectrum (FHSS). However, because Bluetooth shares the 2.4-GHz radio spectrum with 802.11b, HomeRF, and many other consumer appliances (such as cordless phones, microwave ovens, and baby monitors), there is significant potential for interference between these various devices. Bluetooth-based devices require less operating power than 802.11b devices. However, Bluetooth 1.2 has a low throughput of 3 Mbps, has a very small range of about 20 to 50 feet, and is not compatible with other technologies, which are some of its conspicuous disadvantages.

IrDA (Infrared Data Association) is a standard for devices to communicate using infrared-light pulses. This is how remote controls of devices like TV, and DVD players work. Using IrDA, data rates of up to 4 Mbps can be achieved. But, for IrDA to work, the devices must be in line of sight with each other. This means having an access point in every room, which is not too feasible for Home Networks.

HomeRF was founded in 1998 by Compaq, IBM, and HP. It was designed for the small home, not for the large office. The HomeRF Working Group was an alliance of businesses that developed a standard called Shared Wireless Access Protocol (SWAP). A sort of hybrid standard, SWAP is based on the Digital Enhanced Cordless Telecommunications (DECT) standard and the 802.11 wireless-Ethernet standard. Encryption could be used to make data secure. It can achieve data rates up to only 1 Mbps in the 2.4 GHz range. It has a very short range of about 70 to 80 feet. Physical obstructions such as walls and metal objects can interfere with communication. HomeRFs is not well suited for multimedia transmission in home networks.

Wireless LAN is used when referring to 802.11x networks (whether 802.11a, 802.11b, 802.11e, or 802.11g). IEEE 802.11 can achieve data rates up to 2 Mbps in the 2.4 GHz range. It uses the FHSS (Frequency Hopping Spread Spectrum) or DSSS (Direct Sequence Spread Spectrum) technique [12].

IEEE 802.11a communicates at a frequency of 5 GHz and can transmit with data rates up to 54 Mbps. The Physical Layer (PHY) is based on an Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme rather than DSSS or FHSS. The 802.11a Medium

Access Control (MAC) protocol is based on the standard IEEE 802.11 MAC architecture [13] which is consistent across 802.11a, 802.11b, and 802.11g. This standard is attractive for multimedia applications, because of the higher available bandwidth. It can stream content like HDTV and multiple MPEG-2 (DVD quality) video streams because of its high throughput though QoS guarantees are lacking. It has a relatively shorter range, but is less susceptible to interference because of its unique 5 GHz operating frequency. But, it is more expensive than 802.11b.

IEEE 802.11b can achieve data rates up to 11Mbps (equivalent to 10BaseT Ethernet) in the 2.4 GHz range. The PHY layer is based on a Direct Sequence Spread Spectrum (DSSS) modulation scheme. The MAC is based on standard 802.11 MAC architecture. It has an operating range of up to 400 feet. The 802.11b protocol is not interoperable with 802.11a. It features an interoperability mark called Wi-Fi, which is earned via third-party interoperability testing. Wi-Fi certified products will communicate with each other. It is also not as expensive as 802.11a. With a multimedia-enabled MAC, Wi-Fi supports high-speed internet sharing, CD-quality audio and single MPEG-2 streams. But it is limited in its ability to support high-quality multimedia, and it lacks QoS. It cannot support concurrent media streams well. Since the operating frequency is 2.4 GHz, it is also very susceptible to interference with devices that operate in the same range (such as a microwave oven or a cordless phone).

IEEE 802.11g combines the best of 802.11a and 802.11b technologies. It can achieve data rates up to 54 Mbps in the 2.4 GHz operating range. It uses OFDM for data rates above 20 Mbps and uses DSSS for data rates below 20 Mbps. IEEE 802.11g is backward-compatible with 802.11b, which means that 802.11g access points will work with 802.11b wireless network adapters and vice versa. This supports concurrent multimedia streaming, because of its high data rate. But it still lacks QoS and has all the other disadvantages of 802.11b.

2.4 Powerline Networking

Powerline networking is based on the concept of "no new wires." It uses the existing electrical wiring for communication in home networks. It is a very feasible method of establishing home networks because it is inexpensive, easy to install, and very convenient. The convenience is even more obvious because, while not every room has a phone jack, there will

always be an electrical outlet near a computer. In powerline networking, you connect your computers to one another through the electrical outlet. Because it requires no new wiring, and the network adds no cost to your electric bill, powerline networking is the cheapest method of connecting computers in diffcrent rooms. In the past, power lines were considered unacceptable for signal transmission, since the channel was subject to noise, interference, and fading. But, the advancement of signal modulation technologies, digital signal processing, and error control coding has helped reduce channel imperfections and high-speed communication on the power line is now feasible.

Power line communication (PLC) as specified by the HomePlug 1.0 standard provides a data rate of 14 Mbps. It also has a built-in QoS protocol, making it attractive for real-time-streaming applications. Future generations of PLC will provide data rates of up to 100 Mbps, and will support high-quality digital multimedia [1]. There are two powerline technologies. The original technology (called Passport) was developed by a company named Intelogis (Draper, Utah). A new technology (called PowerPacket) developed by Intellon (Ocala, Florida), has been chosen by the HomePlug Alliance as the standard for powerline networking. Intellon's PowerPackct technology, which serves as the basis for the HomePlug Powerline Alliance standard, uses an enhanced form of Orthogonal Frequency Division Multiplexing (OFDM) with forward error-correction, similar to the technology found in DSL modems. OFDM is a variation of the Frequency Division Multiplexing (FDM) uscd in phone-line networking. The present generation of PowerPacket technology is rated at 14 Mbps, which is faster than existing phone-line and wireless 802.11b solutions. Howcvcr, as broadband access and Internet-based content (like streaming audio and video and voice-over-IP) become more commonplace, speed requirements will continue to increase. Along these lines, Intellon's OFDM approach to powerline networking is highly scalable, eventually allowing the technology to surpass 100 Mbps.

The future HomePlug AV standard is being designcd to support distribution of data and multi-stream entertainment throughout the home, including High Definition television (HDTV) and Standard Definition television (SDTV). The main objective is to provide a high quality, multi stream, environment-oriented networking over existing AC wiring, while

also addressing the backward-compatibility with HomePlug 1.0. It would provide the best connectivity at the highest QoS, with data rates of 40 to 60 Mbps. It would also provide solutions for data and network security, which would include encryption and password protection. HomePlug AV will be capable of interfacing with other technologies (like Ethernet, IEEE 1394, DSL, USB, IEEE 802.11, and Bluetooth). It will also be cost-competitive.

In the next chapter, we give a comprehensive description of the HomePlug 1.0 standard and a performance comparison with the 802.11b standard.

CHAPTER 3
POWERLINE NETWORKS

As shown in chapter 2, there are several options for planning the home network, and powerline network is in our opinion a most promising option. This chapter describes PHY and MAC protocols for powerline networks as a home-networking option, and give a comparison with 802.11b wireless networking.

Products using the HomePlug 1.0 standard allowing high-speed communication on low-voltage powerlines have recently started arriving on the U.S. market for home and office networking without the requirement of installing new wires. Effective use of the powerline bandwidth requires robust Physical (PHY) and Medium Access Control (MAC) protocols to mitigate the harsh conditions of the power line channel, and requires the capability to support prioritized multimedia traffic. This chapter describes powerline communications and the HomePlug 1.0 protocol, based on Orthogonal Frequency Division Multiplexing (OFDM) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), along with its changes to allow prioritized channel access. We then present performance results for the HomePlug 1.0 protocol using a simulation model, ideal laboratory measurements with actual HomePlug 1.0 devices, and field tests in a residential building. Simulation and laboratory data rates were around 6 Mbps, and field tests gave rates from 1.6 to 5.3 Mbps at the application level.

3.1 Introduction to PLC Home Networking

Affordable broadband Internet communication to residential customers is now available via cable modems and various flavors of Digital Subscriber Lines (DSL). In turn there is a growing need for in-home networks to share this single full-time Internet access link, while supporting a wide range of digital data and multimedia communication services [14, 15]. While it is a simple matter to use a 10/100 Base-T network hub to link several computers in a single room, or in a small office environment, it is much more challenging to provide network

Table 3.1: Typical costs for various SOHO LAN options

LAN	Characteristic	Limitations	Manufacturers	Costs(USA)
10/100 Base-T Ethernet	Fastest system and low cost NICs	Requires extensive wiring and retrofit	Numerous vendors of NIC cards and Hubs and switches	$75 to $200 / port for retrofit wiring. $60 to $100 new installation
Phone Line	Use existing phone wires	Computers must be near phone jack	Limited number of manufactures	$50 to $100
Wireless	Mobility	Wired infrastructure usually required	Growing number of suppliers	$60 to $250
Powerline	Data port is electrical outlet	New technology products now available	Multiple OEMs using HomePlug specification	$74 to $150

Table 3.2: Data rates of various SOHO LAN options

Network Type	Data Rate
Ethernet/IEEE 802.3	10/100 Mbps
IEEE 802.11a	54 Mbps
HomePlug 1.0	14 Mbps
IEEE 802.11b	11 Mbps
HomePNA 2.0	10 Mbps

connections in several rooms in a typical home [16]. One option, of course, is to re-wire the home with network cabling (typically 10/100 Base-T CAT-5 UTP cabling), which is an expensive proposition, especially if existing homes are to be retrofitted with data communication cables (Tables 3.1 and 3.2 show costs and rates, as of fall 2002).

The second option is to deploy a wireless LAN (Local Area Network) with wireless modems in each device connecting to one or more wireless hubs (infrastructure-based) or to each other (in an ad hoc network). The wireless option is certainly viable, especially for small numbers of nodes in the home/office network; and several companies now offer wireless networking hardware and software typically based on the IEEE 802.11b standard. Unfortunately, experience suggests that a wired infrastructure connecting multiple access points is required to cover the entire home. The third option is to establish a communication channel using the existing low-voltage (110/220 V) power lines that deliver electrical power to outlets and lights in every room (and, depending on the local building codes, to every wall) in the building [17]. A coalition of manufacturers (the HomePlug Powerline Alliance) established a new protocol (the HomePlug 1.0 Standard) to enable the establishment of an Ethernet-class network over powerline channels [18]. It is anticipated that manufacturers of computers,

networking and communication devices, and peripherals will use low-cost integrated circuits based on the HomePlug 1.0 Standard to enable such equipment to act as a node on the home/office network, by simply plugging it into the wall outlet. Thus the outlet, which would normally be a required connection for electrical power, now becomes simultaneously the point of connection for high-speed data communication.

It is also possible to use the telephone wiring (with no new wires), in a similar manner, and perhaps with more attractive channel characteristics. However, phone lines (like Cable TV cabling) appear in only a few rooms in a home at best. Further, there is usually only one phone or cable jack in each room with service. On the other hand, power lines, though ubiquitous throughout the home, are notoriously bad as a communication channel because of electrical noise and interference as well as channel variability depending on the appliances that are in use from time to time. Despite these impediments, tests of the present version of the HomePlug 1.0 powerline devices in some 500 homes show that 80% of outlet pairs will be able to communicate with each other at about 5 Mbps or higher, and 98% will be able to support data rates greater than 1 Mbps. Field tests suggest that the powerline network will provide connectivity in situations where some wireless networks will fail because of large attenuations caused by distance or obstructions (such as intervening walls or furniture). The results of our comparative study seem to support this conclusion.

3.2 Powerline Communications

Since the HomePlug protocol is relatively recent and little information is available on it in the open literature, this section describes it in moderate detail.

3.2.1 Early Power Line Communication Technologies

Efforts to use the powerline as a transmission medium were made 160 years ago [14], but high speed transmission over 10 Mbps was achieved in the mid 1990s. Before this time, the various types of powerlines were assumed to be inherently low-data-rate transfer media. There are several Powerline Communication (PLC) protocols such as X-10, CEBus, and Lonworks. The primary purpose of many of these protocols is not for home networking, but rather for powerline control protocols for home automation, home security, and lighting control.

On the other hand, the HomePlug 1.0 protocol is a high-speed in-home network standard. Although using the same powerline as home automation protocols, the HomePlug 1.0 device can coexist with devices using these other protocols by using a different frequency band than the powerline control technologies [16]. There are also some preliminary high-speed PLC network access devices with limited deployment in Europe, where the interest is primarily in providing Internet access over the last 100 feet, rather than in-home networks [19].

3.2.2 Power Line Medium

Powerlines were originally devised for transmission of power at 50-60 Hz (at most, 400 Hz). At high frequencies, the power line is hostile for signal propagation [20, 21]. Powerline networks operate on standard in-building electrical wiring and, as such, consist of a variety of conductor types and cross sections, joined almost at random. Therefore a wide variety of characteristic impedances are encountered in the network. Further, network terminal impedance tends to vary with communication-signal frequencies and with time as the consumer premises load-pattern varies. This impedance mismatch causes a multi-path effect, resulting in deep notches at certain frequencies [22]. In a typical home environment the attenuation on the power line is between 20 dB and 60 dB, and is a strong function of load.

Electrical appliances are the major sources of noise on power lines, using the 50 Hz electric supply, and generating noise components that extend well into the high-frequency spectrum. Common sources of electrical noise are certain types of halogen and fluorescent lamps, switching power supplies, and motors and variable-resistance dimmer switches. Apart from these, induced radio frequency signals from broadcast, commercial, military, citizen band, and amateur stations severely impair certain frequency bands on the powerline channel. Reliable data communication over this hostile medium requires powerful Forward Error Correction (FEC) coding, interleaving, error detection, and Automatic Repeat Request (ARQ) techniques; along with appropriate modulation schemes and a robust Medium Access Protocol (MAC) to overcome these impairments.

3.2.3 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) [23, 24, 25, 26, 27] is one of the most powerful techniques for data transmission over power lines [25]. OFDM is well known in the literature and in industry [24, 28]. It is currently used in DSL technology [26], and in terrestrial wireless distribution of television signals [29], and has also been adapted for IEEE's high-rate wireless LAN Standards (802.11a [30] and 802.11g). The basic idea of OFDM is to divide the available spectrum into several narrowband, low data rate subcarriers. In this respect, it is a type of Discrete MultiTone modulation (DMT) [31]. To obtain high spectral efficiency, the frequency response of the subcarriers are overlapping and orthogonal (hence the name OFDM). Each narrowband subcarrier can be modulated using various modulation formats. By choosing the subcarrier spacing to be small, the channel-transfer function reduces to a simple constant within the bandwidth of each subcarrier. In this way, a frequency selective channel is divided into many flat fading subchannels, which eliminates the need for sophisticated equalizers [32]. OFDM has the following advantages:

- Excellent mitigation of the effects of time-dispersion
- Very good at minimizing the effect of in-band narrowband interference
- High bandwidth efficiency
- Scalable to high data rates
- Flexible and can be made adaptive different modulation schemes for subcarriers, bit loading, adaptable bandwidth/data rates are possible
- Excellent ICI performance, so complex channel equalization is not required.

For these reasons it is an excellent candidate for powerline communication.

3.3 HomePlug 1.0 Physical Specifications

This section and the next provide a detailed overview of the HomePlug 1.0 specifications at a level appropriate for a protocol engineer. This section describes the Physical (PHY) layer, and the next section describes the Medium Access Control (MAC) layer. Briefly, the PHY uses adaptive Orthogonal Frequency Division Multiplexing (OFDM) with Cyclic Prefix (CP). Both turbo product codes and Reed-Solomon concatenated with convolutional codes are used at various times for forward error correction. The PHY detects channel conditions using

channel estimation, then adapts by avoiding poor subcarriers and by selecting an appropriate modulation method and coding rate for the remaining subcarriers. Three variants of Phase Shift Keying (PSK) modulation [26, 33] are used: coherent Binary PSK (BPSK), Differential BPSK (DBPSK), and Differential Quadrature PSK (DQPSK). A preamble and frame control combination are used as delimiters that start and end long frames, with only the payload portion adapted to the channel conditions. Physical Carrier Sense (PCS) is performed by the PHY layer, and helps the MAC determine when the medium is busy. Fine details necessary to implement a compliant system are available in the official specifications [28].

Connectors are assumed to contact only one line phase (L1 or L2) of the local power line network, and are assumed to be neutral. Connectors may or may not have ground contacts, and the user should be able to connect or disconnect at any time.

3.3.1 Signal Processing

The Physical layer (PHY) of HomePlug 1.0 uses OFDM in a band from approximately 4.49 to 20.7 MHz. The band from 0 to 25 Mhz is divided into 128 evenly spaced carriers, of which 84 fall within the band used (subcarriers 23-106, inclusive). Additionally, eight of the subcarriers (tones) within the usable band are permanently masked to avoid 40 meter, 30 meter, 20 meter, and 17 meter amateur bands, which leaves 76 subbands for use in the U.S.A. The resulting Tone Mask and ToneMap are intended to be alterable to support regulatory requirements in different countries. Spectral compatibility is regulated through the FCC in the US (Part 15 rules), and compliance with radiated power requirements has resulted in -50 dBm/Hz of transmission Power Spectral Density (PSD), much lower than that used by wireless technology.

To avoid ISI (Inter Symbol Interference), a cyclic prefix of the last 172 samples from the Inverse Fast Fourier Transform (IFFT) interval of 256 samples was prepended to the IFFT interval to form a 428-sample OFDM symbol. Using a 50 MHz clock, and 8 samples for roll-off interval, results in 8.4 microseconds per symbol, with 5.12 μs for the raw OFDM symbol and 3.28 μs for the CP.

Figure 3.1 shows an overall block diagram of the OFDM transceiver. Before forming the OFDM symbol in the Analog Front End (AFE), data are scrambled, RS-encoded, convolution

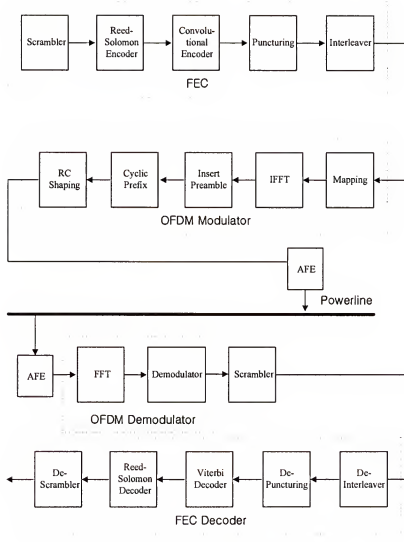

Figure 3.1: The OFDM transceiver

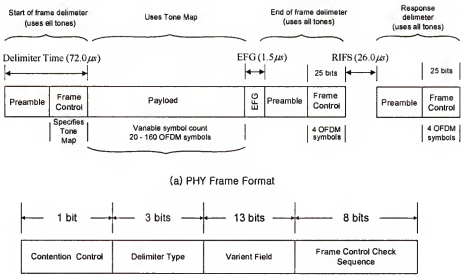

Figure 3.2: HomePlug 1.0 PHY frame format

encoded, punctured, then interleaved on the transmitter. These processes are discussed in more detail below. The AFE consists of a constellation mapping block, an IFFT block, a preamble block, a cyclic prefix block, and a Raised Cosine (RC) block. The mapping block groups data bits and maps them onto a constellation point of the modulation method; it selects the type of modulation and the carriers to be used in the IFFT block, as specified by the Tone Map and Tone Mask. The IFFT block modulates the constellation points onto the carrier waveforms (in discrete time), while the preamble block inserts the preamble.

The CP is added by the Cyclic Prefix block, and RC shaping is used to reduce out-of-channel energy. The physical layer (Figure 3.2) transmits four distinct entities

- The preamble
- Frame control (FC)
- The payload
- Priority resolution signals.

The first two of these are always sent together, and form a delimiter. A delimiter by itself (or a payload surrounded by delimiters) forms a PHY protocol data unit (PPDU), which is discussed in more detail in section 3.3.2.

The preamble consists of seven-and-a-half special OFDM symbols without CP added, and lasts 38.4 μs. It is used for Automatic Gain Control (AGC) and synchronization, as well as forming the phase reference for frame control encoding. The preamble is also used for early detection of the delimiter in Physical Carrier Sense (PCS), and the time needed to determine their presence determines the slot size used by the MAC in the contention period described in Section 3.4.4.

Priority resolution signals consist of six special OFDM symbols without CP, which are, in fact, the same as the preamble symbols, with the polarity reversed. These take 30.72 μs to send; and with processing delay, determine the length of the Priority Resolution Slots (PRS0 and PRS1) used by the MAC to establish prioritized access to the medium (Section 3.4.3).

Data in the four OFDM symbols of the Frame Control (FC) are encoded using a specially designed Turbo Product Code (TPC)[34], and are interleaved with an interleaver distinct from the one used for the payload data. Coherent BPSK is always used for modulation of frame control symbols, and the field takes 33.6 μs to send.

Together with the preamble, the FC forms a 72 μs delimiter, of which there are three basic types: start, end, and response. Formats and functionality are discussed in more detail in Section 3.3.2. The FC of a start delimiter includes two fields needed by the PHY: a length field and the Tone Map Index (TMI). The receiver needs the TMI to know how to demodulate and to decode the payload; and the length tells the receiver how long that demodulation method must be used, before the end delimiter arrives.

Delimiters and priority resolution signals must be detected and decoded correctly by all receivers, so they must use all subcarriers with the same modulation and encoding, no matter who is sending or receiving them. The payload can be and is adapted to the channel conditions by negotiation between the sender and receiver during channel estimation. Channel Estimation determines which subcarriers to use; and for these, which type of modulation and Forward Error Control (FEC) rate to apply.

Depending on channel conditions, a number of combinations of modulation type and FEC rates are available, allowing the sender to adapt to the channel, to improve the data and error rates. Modulation may be either Differential BPSK (DBPSK) or Differential Quadrature

PSK (DQPSK), conveying 1 or 2 raw bits per carrier per symbol, respectively. All subcarriers use the same modulation method.

The PHY payload consists of some number of 20- and 40-OFDM symbol transmission blocks, encoded on a link-by-link basis using a Reed-Solomon/Convolutional concatenated code [35]. These block sizes are needed to combat impulse noise, which can easily damage several OFDM symbols (since differential modulation is used, at least two symbols at a time are lost). The convolutional encoder has constraint length 7; and rates of $\frac{1}{2}$ or $\frac{3}{4}$ (via puncturing) are selectable during channel adaptation. The Reed-Solomon (RS) code has coding rates ranging from $\frac{23}{39}$ to $\frac{238}{254}$. Each combination of modulation and convolutional code rate requires a minimum number of viable carriers to be selected. For DBSK and rate $\frac{1}{2}$, 32 carriers are needed; 16 are needed for DQPSK and rate $\frac{1}{2}$; while 11 suffice for DQPSK with rate $\frac{3}{4}$ convolutional coding.

Before channel adaptation has occurred, the receiver must be able to demodulate and to decode the payload with only *a priori* knowledge. Likewise, to multicast or broadcast a PHY frame, all the receivers must use a common demodulation and decoding method pair. For this reason, and to handle those cases in which transmission using the existing TMs has failed, a special form of modulation and FEC was developed. ROBO mode (for Robust OFDM) is based on DBPSK with extensive time and frequency diversity for robust operation under noisy conditions. ROBO mode always uses all carriers, and also uses a different interleaver than the other modes. Redundancy reduces the rate to $\frac{1}{4}$ bit per carrier per symbol for ROBO modulation. It also uses a different RS code with rates ranging from $\frac{31}{39}$ to $\frac{43}{51}$, and only supports 40-symbol physical transmission blocks.

TMs are used by sender-receiver pairs to adapt to varying channel conditions. A TM lists which carriers a sender will use for unicast to a particular receiver, in order to avoid bad subbands where attenuation is severe or where there is narrowband noise. Each TM also specifies the modulation method and convolutional coding rate to use for the symbols sent. (Note that in HomePlug 1.0, bit-loading is not used; the same modulation method and coding rate are used for all of the indicated carriers.) TMs are not used for frame delimiters, the preamble, or priority resolution symbols, nor is the TM obeyed when ROBO mode is

employed (either for unicast or for multicast/broadcast). The FC frame length field indicates how long the receiver should use the demodulation and decoding methods specified by the tone map before searching for the next preamble. Altogether, eliminating the duplicate ways of achieving the same data rate, 139 distinct physical data rates are available from 1 Mbps. to 14.1 Mbps. With a nearly continuous range of data rates available, channel adaptation allows very good utilization of the bandwidth available, although there is room for improvement using full bit-loading.

3.3.2 PHY Frames

While it is commonly the case to refer to Physical Protocol Data Units (PHY PDUs) and Medium Access Control (MAC) PDUs when discussing protocols, this is not done in the HomePlug 1.0 Specification. We suspect that this is due to the heavy interaction between the PHY and the MAC in the frame control fields of the various delimiters, perhaps due to the lack of a physical address visible to the receiver at the PHY level. Since the physical addresses are so long (48 bits) and the net bandwidth efficiency of the modulation and encoding used for the delimiters is necessarily low, the overhead would be prohibitive if these were included at the PHY layer. Channel adaptation requires that each sender-receiver pair optimize the tone map to the channel conditions on that link, but there is information at both the PHY and the MAC levels that all nodes must see. Both MAC and PHY need length information, and the MAC also needs contention control and priority information. The compromise used in the HomePlug 1.0 standard is to violate strict layering for the sake of efficiency, and allow the universally readable FC field to hold information needed by both layers. For this reason, the delimiter FC fields appear in the PDUs of both layers. We will proceed to call the PHY frames PPDUs, and the MAC frames MPDUs, and not worry that the FC appears in both.

As shown in Figure 3.2, a long PHY Protocol Data Unit (PDU) starts with a Start-of-Frame delimiter (SOF) followed by the payload, a 1.5 μsec. End-of-Frame Gap (EFG) and an End-of-Frame frame delimiter (EOF). The EFG is a delay inserted to allow for processing time. The EOF helps in collision detection and recovery, in addition to its MAC functions. Payload size in data bits is determined not only by the length (in increments of 20 symbols as required by the PHY transmission blocks, or 40 symbol blocks for ROBO mode), but also

by the modulation method and the coding rate used for that transmission. Short PPDUs consist solely of a response delimiter.

Each 72 microsecond frame delimiter consists of a preamble (see Section 3.3.1) followed by a Frame Control (FC) field. The four OFDM symbols of frame control provide 25 bits of control data per frame control field. A type field distinguishes SOF, EOF and response delimiters, and in SOF and EOF, includes whether or not a response is expected. All delimiters have an 8-bit Cyclic Redundancy Check (CRC) as a Frame Control Check Sequence (FCCS) to detect errors in the frame control field.

The SOF FC includes the length of frame (encoding the number and size of PHY transmission blocks) and the Tone Map Index (TMI) that the intended receiver should use to find the Tone Map needed to demodulate and decode the payload. Others attempting to decode the payload using a different TM (with the same TMI) are very unlikely to do so correctly, while the intended receiver will be able to confirm its status by checking the destination address in the decoded payload contents.

It is necessary for the PHY to know what type of modulation and decoding is used to decode the PPDU payload properly. This information is contained in the SOF in the TMI, which indexes into each node's Tone Map Table where the modulation type and coding rates negotiated during channel adaptation are stored. The PHY also needs to know how long it should use this tone map before it looks for the EOF; this information is carried in the length field of the SOF FC.

3.4 HomePlug 1.0 MAC Layer

The HomePlug 1.0 MAC Layer uses channel access based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to transport data from 46 to 1500 bytes long from encapsulated IEEE 802.3 frames as MAC Service Data Units (MSDUs).

A four-level priority scheme enforces strictly prioritized access (higher priority traffic will be able to gain access to the medium as soon as a lower priority segment has been sent). Segmentation limits delay for high priority traffic, and contention-free access modes support low jitter requirements. Contention for the channel is limited to those nodes that survive the Priority Resolution Period.

Stations inferring a collision must invoke a backoff procedure, by which they successively increase the amount of random delay they wait in the contention period up to some maximum, depending on the priority level of their data. Different than other CSMA/CA methods, HomePlug 1.0 also uses the number of times that a station has deferred to other stations at the same priority level to infer the amount of traffic present at that level and to adjust the backoff range accordingly.

The MAC segments longer MAC Service Data Units (MSDUs) to limit transmit time as the PHY rate is lowered adaptively. Each unicast segment is acknowledged, and "Partial ARQ" is an option for multicast/broadcast segments to let the sender know that at least one station received the segment correctly. Segment bursting avoids contention for the medium on every segment, yet allows for preemption by higher priority traffic.

MAC management functions support channel estimation and rate adaptation, as well as key management for cryptographic isolation of logical networks. All stations in a logical network share the same Data Encryption Standard (DES) key, called a Network Encryption Key (NEK). This is needed since multiple apartments may share the same transformer, which allows nodes in one apartment to hear PPDUs sent by nodes in a neighboring apartment over this broadcast medium. An IEEE-registered Ethertype allows MAC management information to be passed transparently.

In the interest of brevity, MAC functions of bridging, link status, and parameter and statistics reporting have been omitted.

3.4.1 Carrier Sense and Collision Detection over Power Lines

Due to attenuation, noise, and channel adaptation, it is difficult to use only Physical Carrier Sense (PCS) as is used in many other CSMA system such as Ethernet. The HomePlug 1.0 PHY layer reports Physical Carrier Sense (PCS) by detecting preambles or priority slot assertions, while the MAC layer maintains Virtual Carrier Sense (VCS) using the length field of the SOF frame control, along with information on whether a response is expected or not (present in both the SOF and the EOF frame control).

Likewise, direct collision detection as used in Ethernet is unreliable due to attenuation and other factors, so collisions can only be inferred from a lack of response after a frame is

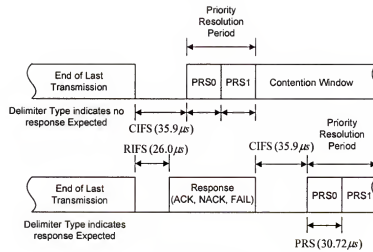

Figure 3.3: Interframe spacing in HomePlug 1.0

sent. This makes collisions very costly compared to CSMA/CD systems, so they must be avoided by being less aggressive when the medium is busy. Rather than transmit as soon as the medium becomes idle as in standard Ethernet, HomePlug 1.0 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Similar to IEEE 802.11, following each frame there is typically a contention period consisting of a succession of short slots (35.84 μsec. for HomePlug 1.0) during which a station may initiate transmission, provided that it has detected no other station that has started sending before that slot (i.e., deferred).

3.4.2 Interframe Spacing and Timing

There are several points at which the protocol requires a delay for processing or to change from receive to transmit mode. When a response is expected (as indicated by both the SOF and the EOF FC fields), the responding station waits for a Response InterFrame Space (RIFS) of 26.0 μsec before transmitting its response. After the response, if one is expected, or after the EOF, if no response is expected, all stations consider the medium to be busy for a Contention InterFrame Space (CIFS) of 35.84 μsec before the Priority Resolution Period begins. Each 35.84 μsec Priority Resolution Slot may contain a Priority Resolution Signal lasting 30.72 μs. sent by one or more stations. Due to tight synchronization and minimal propagation delays, these signals are additive, and the slots have their own processing delay built in.

As shown in Figure 3.3, the RIFS and CIFS are needed for propagation and processing times. The Extended InterFrame Space (EIFS) is used when a station is not sure of the state of the medium, for example, while it listens for another station to start transmission. It accounts for the maximum time that a station could be transmitting by including the nonROBO maximum frame duration along with the various delimiters, priority slots, CIFS, RIFS, and EFG. All of this amounts to 1695.0 μsec. EIFS is also used to determine how long the channel is considered busy after a collision, when a station defers to higher priority traffic or a Frame Control error (since the length of the frame cannot be determined reliably for more accurate VCS).

3.4.3 Priority Resolution

Before the contention period, there is a Priority Resolution Period (PRP) consisting of two 35.84 μsec. Priority Resolution Slots (PRSs). Using the PRP, only the stations with the highest priority traffic to send may contend for the medium in the contention period.

Stations contend using PRS0 and PRS1 to determine maximum priority traffic on the network. Four priority levels are supported: CA3 and CA2 for time-sensitive, high priority traffic, and CA1 and CA0 for lower priority traffic. If the EOF delimiter or Response delimiter of the frame immediately preceding the PR period has the contention control bit set, then any nodes with the same or lower priority defer. Otherwise, CA3 and CA2 nodes assert PRS0, which will cause CA1 and CA0 nodes to defer. CA3 nodes also assert PRS1, which will cause CA2 nodes to defer; if PRS0 is not active, then CA1 nodes will assert PRS1, which will cause CA0 nodes to defer. Only nodes from the highest (winning) priority class contend for access to the medium using the contention window. Priorities should be assigned according to the 802.1D guidelines. This allows HP 1.0 networks to operate with RFC 2205 RSVP (Resource Reservation Protocol) and the internet draft standard Subnet Bandwidth Manager (SBM) to provide differentiated quality of service (diffserve) for multimedia traffic [36, 37]. CA3 is used for VLAN tag priority 6 or 7 (network control and extremely delay-sensitive traffic such as voice), and CA2 is used for VLAN tag priority 4 or 5 (delay-sensitive traffic such as video and audio, and important business applications subject to admission control). CA1 is used for "excellent effort" (highest quality best effort service) and is the default level. CA0

is for standard LAN traffic (when this is labelled as such) and background traffic. MAC management entries may also use the priority necessary (e.g., for channel estimation requests and replies).

3.4.4 Channel Access

The contention period is used by the Backoff Procedure, which is disabled during segment bursting or contention-free access (see below). First, PCS/VCS is used to detect the medium state and wait either until it is idle, or until the priority resolution period (in which case the station asserts its priority unless it must defer), or until it has won the PRP and can contend for the medium in the contention window.

When a station first starts contending for the channel, it randomly picks one of the first eight contention slots following the PRP to start its transmission, setting a Backoff Counter (BC) to the number of slots to leave empty for others to use. If no other SOF delimiters are detected before the selected slot arrives, then the station starts transmission in that contention slot. Otherwise it defers and sets its Deferral Counter (DC) according to the schedule shown in Table 3.3. As unused slots go by in contention periods at the same priority level as the traffic waiting to be sent by the station, the backoff counter is decremented until one of two things happens. If the BC reaches zero, the station starts transmission, then awaits a response if one is expected. If the DC reaches zero, then so many stations at the same priority level have made their presence known that the sender randomly picks a new value for the BC from the next larger range of values (depending on the priority level of its data), in much the same way that it would if it inferred a collision. This allows the extra information from deferrals to be used to avoid costly collisions.

When a station sends a frame and either does not expect a response or receives a matching ACK from its destination, then the frame has been sent successfully, so the next frame is readied for transmission and the BPC is reset to 0. If it was the last segment in a service block, then success is reported to the host interface.

If a valid FAIL response is received, and the maximum number of FAIL retries (between 0 and 6) has not been exceeded, then the station waits an extended time (10 ms.) before resuming its efforts.

Otherwise, if it either receives a NACK or it infers that a collision has occurred, the station invokes the backoff procedure by increasing the DC value and the contention window size in accordance with the backoff schedule, up to a maximum of 32 for CA3 and CA2, or 64 for CA1 and CA0, and picking a new random delay time for the BC. If the station has tried the maximum number of attempts that can be made using the destination-specific Tone Map, then the mode is switched to ROBO and further attempts are made to deliver the frame. Switching to ROBO mode may require resegmenting the service block (see Section 3.4.6). If the limit is exceeded on the number of transmission attempts that may be made (either in total or for ROBO mode, for NACKs or for collisions), then the frame is discarded and failure is reported.

Table 3.3: Backoff schedule

BPC	DC	CW	
		CA3 and CA2	CA1 and CA0
0	0	7	7
1	1	15	15
2	3	15	31
> 2	15	31	63

In Table 3.3, BPC is the Backoff Procedure Counter, which counts the number of times that the Backoff Procedure has been invoked due to collisions or deferrals. The BPC is reset to 0 after a FAIL, as the amount of traffic is expected to change after the long delay. DC is the Deferral Counter and CW is the Contention Window maximum (the minimum is zero, so the CW size is actually CW+1).

Collisions are inferred under several circumstances. First, if no response is detected when one is expected, then a collision is assumed, although this could be due to a bad channel. Even if a delimiter is detected, if the DC field of the delimiter is bad, or if the FC does not indicate that it is an ACK, NACK, or FAIL when a response is expected, then a collision is inferred. Finally, FAIL and ACK responses contain a Response FCS (RFCS) field that echoes the 10 or 11 (respectively) LSBs of the FCS from frame they acknowledge. If the RFCS field does not match the one sent, then the sender assumes a collision has occurred.

3.4.5 MAC Error Control

The MAC implements a stop-and-wait ARQ error control method. Acknowledgement and retransmission are performed on a per-segment basis. Expectation of a response is indicated in the FC fields of both the SOF and the EOF delimiters. The response is sent by the destination in a short format MPDU, consisting of a solitary response delimiter. Three types of responses are used: ACK, NACK, and FAIL. All three include a 10- or 11-bit Response FCS (RFCS) field, which is a copy of the LSBs of the 16-bit FCS of the MPDU for which the response was sent, as well as the Channel Access Priority (CAP), which is used for contention control and preemption.

An ACK response has an 11-bit RFCS, and only if the RFCS matches the least significant 11 bits of the FCS of the transmitted frame is that frame considered acknowledged. Otherwise, the sender treats it as a collision. NACK and FAIL have 10-bit RFCS fields. NACK is used to indicate that a frame was received with errors, as indicated by the FCS, while FAIL is used to indicate that the receiver has no buffers available for reassembly of the service block or that the segment was received out of order. NACK and FAIL with valid RFCS surely indicate failure, and the absence of a valid ACK when one is expected is also taken to indicate a failure or collision. Frames receiving a NACK or no response may contend for retransmission right away, but a FAIL response requires the sender to wait a longer time (the 10 msec FAIL delay) before retrying, in the hope that the receiver has finished reassembling the service block on which it was working earlier, and will have the resources available to begin reassembly of the service block to which the frame belongs. In fact, only higher priority frames may be sent by that station to the destination address that responded with a FAIL. If the segment receiving the FAIL response was not the first segment, then the entire service block transmission attempt is aborted and the sender starts over. Stations attempt to transmit the frame until the retry limit is exceeded or the transmit lifetime is exceeded.

Optional, partial ACKs are available for multicast and broadcast frames; the sender can specify any station in its Logical Network (not just those in the multicast group) to respond to a multicast or broadcast frame. The Multicast with Response MAC management entry of the service block has the actual 6-byte multicast destination address, while the DA in the

layer management MAC frame is a proxy for the multicast and will generate a response if the delimiter type indicates that one is expected. In the case of partial ACKs, FAIL may be treated as an ACK.

A tight response timeout interval is used to decide how long to wait for a response before inferring that a collision has occurred. A valid ACK inspires the node to send the next segment (if there is more of the SB to send) or to report success (if this was the last segment of the SB).

3.4.6 Segmentation and Reassembly

A service block is segmented into MPDU frame bodies as needed, depending on the number of bytes that an MPDU can carry due to the 160-symbol payload limitation and the data rate determined by the Tone Map. Each MPDU includes the MSDU's DA and SA in its frame header, and each has its own SC and FCS. Only the last segment has B-Pad, as all the others should completely fill their MPDU frame body. The Segment Control (SC) field is always present, even if the SB is not segmented (i.e., it is a one segment service block). SC includes the segment length in bytes exclusive of B-pad, SC, and LSF. Segment bursting is used to send all segments of an SB in as short a time as possible (modulo preemption by higher priority - see Section 3.4.7).

The Segment Control (SC) field of the frame header includes a Sequence Number (SN), a segment count, and a Last Segment Flag (LSF). These are used to detect duplicates and to recover. The SN is the same for all the segments in the same service block, and is incremented for each new service block. The Segment Count indicates which segment within an SB the MPDU holds, starting with a value of 0 for the initial segment. LSF indicates the last segment in a service block.

For each SA and priority, a receiver stores the most recent ⟨SA,SN,SC,LSF⟩ tuple. List entries are compared to incoming frame header fields to detect duplicates and omissions. New ⟨SA,priority⟩ pairs create new list entries, with an ACK if it is the first segment. Likewise, the first segment of a new received SN causes the list to be updated. Segments received in correct order naturally generate ACKs and update the list; and when the LSF is set, indicating that reassembly is complete, the reassembled service block is passed up for decryption. Most

recent segment duplicates overwrite the reassembly buffer segment and generate an ACK, while older segments or segments that would leave a gap in the reassembly buffer cause the receiver to send a FAIL response and flush the reassembly buffer. This forces the sender to start transmission of the SB over from the first segment.

Responses are only sent for MPDUs requiring a response, and a reassembly timer is used to prevent a partially reassembled SB from occupying resources indefinitely. Every station is required to have at least one MPDU reassembly buffer with timer. More than one is allowed, but each buffer must have its own timer.

3.4.7 Segment Bursting and Contention-Free Access

Segment Bursting uses the contention control and channel access priority fields in the delimiter FC to allow a station to send segments belonging to the same service block without repeatedly contending for the channel. Stations with higher priority traffic can preempt a segment burst by asserting the priority bits between segments in the burst. Segment Bursting is limited to two consecutive MPDUs at CA3, in order to provide low jitter for CA3 traffic. This mechanism allows for efficient use of the medium while still preserving high quality differentiated service.

To use segment bursting, a station contends as usual. Once it gains access, it sets the CC bits in the SOF and EOF FCs to 1, and inserts its MPDU's priority in the CAP field of the EOF FC. After each segment is sent (and acknowledged, if required), the Priority Resolution Period (PRP) is open to stations with traffic at a higher priority level. The sender also asserts its priority in the PRP, listening for a station with higher priority traffic. As long as it is not preempted, the station continues to transmit the rest of the segments in the service block right after the PRP. In the MPDU containing the last segment, the CC bit in FC is cleared to allow normal contention to occur. If the sender is preempted, then it goes back to priority resolution and contention as usual.

A more restricted way to limit contention is also supported. Contention-Free Access (CFA) is only available to stations with CA3 traffic, and allows a station to send all of its service blocks (even to different DAs) at level CA3 using CC=1 in FC. It is limited to seven

consecutive MPDUs per CFA burst. CC is reset to 0 in the FC of the last segment of the last MPDU in a CFA burst.

3.4.8 Privacy and Key Management

Power lines are shared from the transformer to all of the residences served by the transformer, so it is possible for a residence to hear the PLC transmissions of a nearby residence. It is therefore necessary to protect the privacy of users cryptographically, since installing low-pass filters would to some extent negate the cost advantages of the technology. To this end, nodes form Logical Networks (LNs) based on cryptographic isolation.

HP 1.0 uses DES (FIP Std. Publication 46-3) in Cipher Block Chaining (CBC) mode. Keys are generated from passwords using the PBKDF1 function from PKCS#5 v2.0, Password-based Cryptography Std., with MD5 as the underlying hash algorithm. Stations store and retain both their default key (for re-key operations only) and any Network Encryption Keys (NEK) received (for any other transmissions) in nonvolatile memory.

All transmissions within a logical network are encrypted with the NEK that defines that logical network. To participate in a LN, a station must have the NEK for it.

3.5 HomePlug 1.0 Test Results

This section presents simulation and ideal laboratory performance results[4] for the HomePlug 1.0 powerline network. Based on information presented in Sections 3.3 and 3.4, an event-based C program was developed to simulate the HomePlug 1.0 protocol. In the rest of this section, we present the simulation results as well as ideal laboratory measurements of the HomePlug 1.0 protocol performance.

3.5.1 Simulation Results

For the simulation test, we used QPSK modulation with a $\frac{3}{4}$ coding rate and a TCP segment and a UDP packet size of 1460 bytes, both with 100 μsec average inter-arrival time. All traffic was treated as priority CA0 packets.

[4] An early version of these results was presented [38].

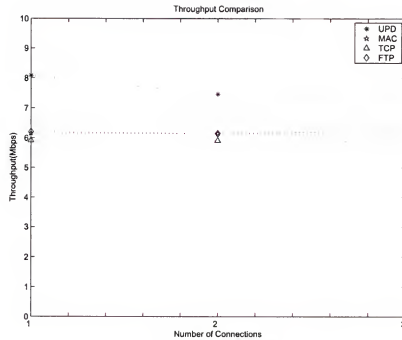

Figure 3.4: Throughput results

Figure 3.4 gives the simulation results for different numbers of UDP and TCP connections. We observed that UDP traffic obtains a rate of 7.5 Mbps to 8 Mbps for up to 3 nodes, while both MAC and TCP throughput ranged from 5.9 Mbps to 6.1 Mbps.

In the TCP traffic simulation, nodes need to wait until they receive proper ACKs and they must also share the bandwidth with response frames. The TCP performance was slightly lower than that of UDP. In Figure 3.4, the MAC throughput represents the total number of transmitted bytes divided by the simulation time regardless of successful delivery. The TCP throughput includes only the successfully delivered data and ACKs.

3.5.2 Performance Measurements in an Ideal Laboratory Setting

To compare the simulation results with a real HomePlug 1.0 network, we conducted the following ideal laboratory experiment as illustrated in Figure 3.5 .

All computers are connected to the powerlines via the same power strip to give an almost ideal powerline channel. To evaluate the throughput of this real PLC network, we conducted the following experiment. A 215,502,106 byte file was placed on the server running an FTP daemon (The large file size was chosen to minimize hardware uncertainty and human error.)

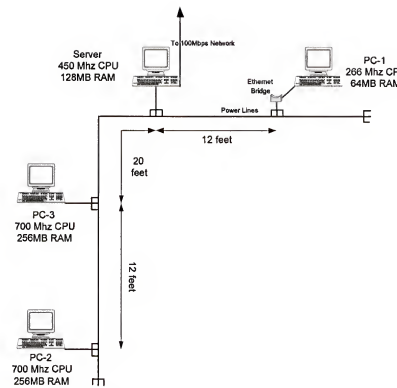

Figure 3.5: Ideal laboratory test setup

Client computers made FTP requests for the file. We tested different numbers of FTP connections, up to 3, using individual client machines in our PLC network. The experimental results are also given in Figure 3.4. The aggregated traffic in the table is calculated by adding all observed data rates of all connections. The results show that the real PLC network performance is about 6 Mbps with minor variations as the number of FTP connections increased from 1 to 3. Thus the real PLC HomePlug 1.0 network was observed to provide throughput comparable to those predicted by the protocol simulation model.

3.6 Field Performance of HomePlug 1.0 in a Residential Setting

This section reports on the result of a field test using HomePlug 1.0 devices which was conducted in a typical Florida home[3] . The objective of the test was to determine the performance of HomePlug 1.0 in a practical residential setting.

[3] A short version of some of these results was presented [39].

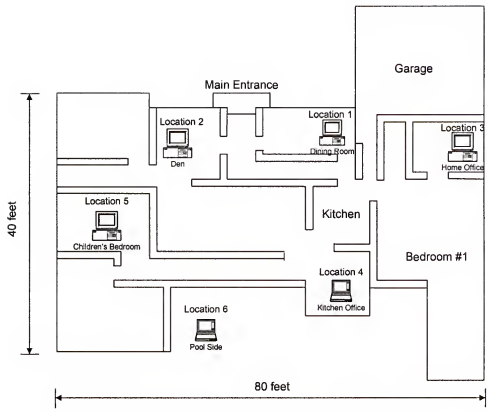

Figure 3.6: Plan of residential test setup

3.6.1 Test Setup

The field test was conducted in a 2700 square feet, 10 year old house in Gainesville, Florida (see Figure 3.6 for floor plan and test locations).

For this test, we used two laptop computers. One machine was a 700 MHz Pentium III equipped with a HomePlug 1.0 powerline USB bridge. The other machine was a 500 MHz Pentium II equipped with a HomePlug 1.0 powerline Ethernet bridge.

These tests were designed to measure the data transfer capability of the residential power line network. To ensure that the results obtained would accurately reflect user experience, we used the following scenarios for testing.

- Scenario-1: FTP – We used the WSFTP program to do a file transfer. This utility is very widely used. We set up this utility with the following parameters:

  Transmit Buffer Size: 4096 bytes

Receive Buffer Size: 4096 bytes

File transfer size: 40 Mbytes;

- Scenario-2: TCP – We used the WSTTCP program to test the TCP performance. WSTTCP is a popular program for TTCP. We set up this utility with the following parameters:

  Buffer Length: 4096 bytes

  Number of Buffers Sent: 5000

  Total data exchange: 20 Mbytes

  Protocol: TCP.

3.6.2 Test Results

Table 3.4 shows the HomePlug 1.0 network throughput. Note that the powerline network exhibited full connectivity over the entire home. Furthermore, the powerline transfers were always at a near constant rate with very little fluctuation.

Table 3.4: Field test throughput results

Transmitter	Receiver	Distance between transmitter &receiver	Powerline	
			WSFTP Throughput (Mbps)	TTCP Throughput (Mbps)
Laptop 1 (Dining Room)	Laptop 2 (Dining Room)	~2 feet	4.2	5.2
Laptop 1 (Den)	Laptop 2 (Dining Room)	~23 feet	4.5	5.3
Laptop 2 (Office)	Laptop 1 (Kitchen)	~35 feet	4.0	4.5
Laptop 1 (Kitchen)	Laptop 2 (Office)	~35 feet	3.1	3.1
Laptop 1 (Children's Room	Laptop 2 (Office)	~70 feet	1.9	1.8
Laptop 2 (Office)	Laptop 1 (Children's Room)	~70 feet	4.1	3.9
Laptop 1 (Swimming Pool)	Laptop 2 (Office)	~60 feet	2.0	1.6
Laptop 2 (Office)	Laptop 1 (Swimming Pool)	~60 feet	2.4	2.8

For larger distance separations the performance dropped and the observed throughput was not the same for the forward link and the reverse link. Sometimes, the throughput on a given link gave a performance twice that achieved in the other direction. The FTP throughput in these tests ranged from 1.9 Mbps to 4.5 Mbps, while the TTCP throughput was between

1.6 Mbps to 5.3 Mbps. The maximum TCP throughput of 5.3 Mbps obtained in this practical test compares quite well with the ideal laboratory measurement of 6 Mbps for FTP and the TCP simulation performance of 6.1 Mbps.

3.7 Performance Comparison

This chapter provided a comprehensive description of the powerline environment and the PHY and MAC protocols for the HomePlug 1.0 Standard. Simulation and laboratory testing demonstrate a throughput of about 6-8 Mbps. A HomePlug 1.0 powerline LANs showed 100% connectivity in a 2700 square feet home and reliable throughput of 1.6 Mbps to 5.3 Mbps at the application level. Throughput for the powerline network is in general not symmetric for a pair of nodes. Additional studies and more extensive testing are currently under way in both laboratory and field conditions.

In-home powerline communications have the potential for significant improvements. These enhancements include higher frequency bands, higher level modulations, better forward error correction code, etc. In October 2002, the HomePlug Powerline Alliance announced plans for the development of next generation powerline specifications. As mentioned in chapter 2, the new protocol, called HomePlug AV, will operate at 100Mbps and will be designed to support distribution of data and multi-streaming entertainment including High Definition television (HDTV) and Standard Definition television (SDTV) throughout the home.

In the next chapter, we present a study of the MPEG-2 standard for video which will make use of the home network infrastructure such as powerline networking.

CHAPTER 4
MPEG-2 TRAFFIC

Since MPEG is the standard for compressed multimedia video, it is important to understand the structure of the MPEG standard in order to design home networking multimedia communication system. There are two types of MPEG-2 traffic service classes, namely, Variable Bit Rate (VBR) and Constant Bit Rate (CBR).

A primary concern of VBR MPEG traffic is maintaining consistent quality with varying bit rate. It is not easy to predict the required bandwidth, but VBR traffic provides the best possible quality of the encoded media. Sources are expected to transmit at a rate which varies with time [40].

The bit rate over time for CBR keeps close to the average bit rate, and in this case it is easy to know the required bandwidth. But, CBR service is inconsistent in quality. CBR MPEG traffic is intended for real-time applications, i.e. those requiring tightly constrained delay and delay variation, as would be appropriate for voice and video applications. The consistent availability of a fixed bandwidth is considered appropriate for CBR service [40].

An example of MPEG-2 traffic stream is Digital Versatile Disc (DVD). DVD-Video is a format for the DVD-Video player to support MPEG-1, MPEG-2, Dolby Digital, DTS, and other formats. DVD-Video can contain CBR or VBR. Generally, commercial DVD-Video uses VBR compressed digital video because it needs to maintain good video quality. Table 4.1 shows the different for parameters NTSC and PAL video.

Table 4.1: Different specification between NTSC and PAL video

	NTSC	PAL
Region	United States	Europe
Picture Dimension	720×480	720×576
Interlaced frame/sec	29.97 fps	25 fps

The maximum video bit rate is 9.8 Mbps for DVD traffic. The average video bit rate is about 4 Mbps (but depends entirely on the length, quality, amount of audio, etc.) [41].

4.1 Overview of MPEG-2

Moving Picture Experts Group (MPEG) refers to a family of specifications developed by the International Standards Organization (ISO) and the International Electro-Technical Commission (IEC). MPEG specifies a digital compression format for the coding of moving pictures, audio and related data (e.g., movies, video, music). MPEG is a working group which was established in 1988 provides a framework for coding moving video and audio and significantly reducing the amount of storage with minimal perceived difference in quality [41, 42].

MPEG-1 is divided into three main parts which are audio and video compression coding, and system management and multiplexing for audio and video data. This forms the basis for the coding used for video CD and downloadable video over Internet. The primary purpose of MPEG-1 is digital data storage and a low error probability is assumed. It is interesting to note that MPEG-1 audio layer 3 is MP3 which is well known audio format. MP3 is not MPEG-3 [41, 42].

The MPEG-2 standard includes the MPEG-1 specification, provides for backward compatibility with existing MPEG-1 standard, and support for interlaced pictures, better error recovery possibilities, more chrominance information formats, non-linear macroblock quantization as well as the possibility of higher resolution DC components. Originally, MPEG-3 was the standard for HDTV, but it is merged to MPEG-2 because MPEG-2 can support the required high resolution coding. It is interesting to note that MPEG-1 is more efficient than MPEG-2 when the coded bit rate is less than 2 Mbps [41, 42].

4.2 Introduction to MPEG

MPEG frames consist of I, B, and P frames. The I frame is the Intra coded frame which contains the complete image data for that frame. The P frame is the Predictive coded frame which contains only the data that relates to how the picture has changed from the previous frame. The B frame is the Bidirectional coded frame which contains only data to interpolate the position and color of each pixel from the closest surrounding frames. Figure 4.1 shows how a MPEG file is composed.

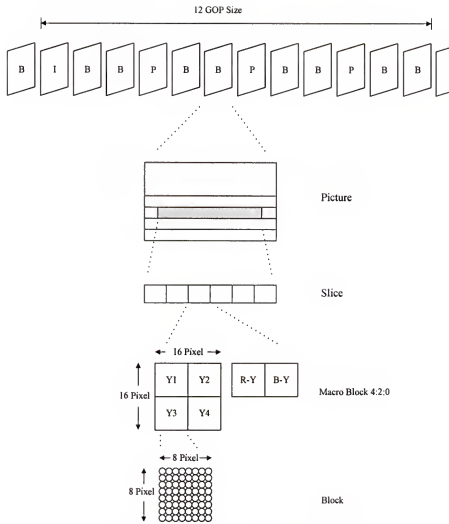

Figure 4.1: Structure of MPEG-2 video data

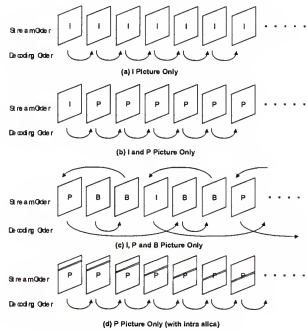

Figure 4.2: Frame sequence type

The MPEG-2 video data structure has group of pictures (GOP), picture, slice, macroblock, and block, as shown in Figure 4.1. This treatment is a summary from several sources [41, 42, 43].

- GOP(Group of Picture): The group of picture layer is optional for MPEG-2. It begins with a start code and a header. The header carries time code for the first picture of the GOP, editing information, and optional user data. The first encoded picture in a GOP is always an I picture. A typical expression of GOP for 12 pictures are I B B P B B P B B P B B, but it is not mandatory to follow this. There is no GOP restriction for MPEG-2, which is different from MPEG-1.

  The frames usually do not show typical order. In Figure 4.2, the most common order of frames are shown. Figure 4.2(a) has only I frames. It is not well compressed because I frames do not use other frame information to decode the picture. Although it does not have good compression ratio, it has low data processing delay. Figure 4.2(c) has worse data processing delay and a good compression ratio.

- Picture: The source picture is a contiguous rectangular array of pixels. A picture has two different types. One is intra coded picture that is coded without previous and future

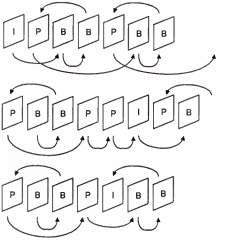

Figure 4.3: Common decoding order

frame information. Other is nonintra coded picture that is coded with other picture information [43].

- Slice: Pictures are divided into slices. A slice consists of an arbitrary number of successive macroblocks (going from left to right), but is typically an entire row of macroblocks. A slice does not extend beyond one row. The slice header has address information that allows the decoder to reconstruct the slice into a picture [42].
- Macro Block: Each macro block has a 16 x 16 array of luminance (Y) which has 4 blocks. The chrominance (Cr, Cb) block size will vary depending upon the chrominance pixel structure indicated in the sequence header.
- Block: A block is an 8 x 8 array of pixels. Four luminance blocks plus a number of chrominance blocks that depends on the chrominance pixel structure indicated in the sequence header comprise a macro block. A block is the basic building unit of the DCT (Discrete Cosine Transform).

4.3 Color Model Transformation

(a) RGB Model: Red, Green, and Blue

The colors red, green, and blue are three primary colors in additive light models and used on a computer display using the reflectance or emission characteristics of light.

(b) CMY Model: Cyan, Magenta, and Yellow

The color model CMY or CMYK is used in color printer using the characteristics of absorption.

(c) YIQ Model: Y: luminance I : R-Y (chrominance: Inphase) Q: B-Y (chrominance: Quadrature)

The color model YIQ is used in NTSC color television. Y component represents the luminance and the black and white television interprets Y component.

The color coordinate conversion between RGB and YIQ is linear.

$$\begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & -0.311 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \tag{4.1}$$

(d) YCrCb Model: Y: luminance Cr : Color Red Cb: Color Blue

The color model YCrCb is used in Digital Video. There are two advantages: This color model can be easily applied reducing the transmit bandwidth and has backward compatibility with black and white television.

The color coordinate conversion between RGB and YCrCb is shown in Eq. (4.2).

$$\begin{aligned} Y &= 0.299R + 0.587G + 0.114B \\ Cr &= 128 + 0.713x(R - Y) \\ Cb &= 128 + 0.565x(B - Y) \end{aligned} \tag{4.2}$$

4.4 DCT and BMA

The human vision system exhibits some characteristics that are exploited by MPEG video compression. One of these is that large objects are much more noticeable than details within them. In other words, low spatial frequency information is much more noticeable than high spatial frequency information.

MPEG video compression discards some high spatial frequency information - information which is less noticeable to the eye. The first step in this process is to convert a static picture into the frequency domain. The Discrete Cosine Transform (DCT) performs this

transformation.

$$F(\mu,\nu) = \frac{C(\mu)}{2}\frac{C(\nu)}{2}\sum_{y=0}^{7}\sum_{x=0}^{7} f(x,y)cos[(2x+1)\mu\pi/16]cos[(2y+1)\nu\pi/16] \quad (4.3)$$

where μ and ν are the horizontal and vertical frequency indices, respectively, and the constants, $C(\mu)$ and $C(\nu)$ are given by:

$$C(\mu) = 1/\sqrt{2} \quad \text{if} \quad \mu = 0 \quad \text{and} \quad C(\mu) = 1 \quad \text{if} \quad \mu > 0 \quad (4.4)$$

The DCT conversion process does not affect the image quality loss. Image quality loss occurs as a result of the quantization [43]. This will be discussed in the next section.

The MPEG-1 and MPEG-2 uses block based motion estimation and it is called BMA (Block Matching Algorithm). For each block, the BMA searches for the best matching block from the neighboring picture and calculates the motion vector and estimation error. It has enough information to decode the MPEG and a good compression ratio. There are several works related to how the calculation complexity can be reduced with the optimized comparing sequence. For example, there are the following: 2-D logarithmic search [44], three step search [45], conjugate direction search [46], cross search [47], etc.

By applying BMA to the picture, the P and B frames are generated. That is why the P and B frame needs information from other frames to decode while the I frame already has full information to decode.

4.5 Quantization and Huffman Coding

The second step for MPEG video compression is Quantization. This is performed to reduce unnecessary high frequency information. As mentioned above, high frequency information is not critical for human eyes. After the image is DCT transformed, it is divided into 8x8 blocks. These blocks are then encoded individually. The blocks on the top left corner are encoded with more bits to keep the important information or energies. In the bottom right hand corner, the blocks are encoded with fewer and fewer bits. This is the usual DCT quantization method.

Huffman coding is applied to compress the quantized DCT values more efficiently. Huffman coding is a lossless compression method. Huffman coding is a technique which attempts

to reduce the average code length with variable code length. In order to reduce the average code length, symbols are allowed to be of varying lengths, and the shorter codes are assigned to the more frequently used symbols and longer codes are assigned to the less frequently used symbols [43].

Using this information of MPEG-2, we will now proceed in the next chapter to studying VBR DVD traffic characteristics for a variety of typical movie genres. This information will be useful in a DVD traffic generation for uses in simulators and test beds of multimedia communication network.

CHAPTER 5
MOVIE CHARACTERISTICS

The DVD frame information used in this dissertation was collected from commercial DVD titles. The DVD titles are chosen with varying genres, running times, and production companies. In this chapter, the frame size extraction from commercial DVD is described and the DVD traffic information is derived empirically.

5.1 DVD Frame Size Extraction

A C program [48] was used to extract the frame type and frame size from the DVD movie. This program opens the binary MPEG-2 file in Hex format, seeks the specific Hex start code, and checks the distance between those specific Hex codes. Most commercial DVD titles are encrypted by CSS which stands for Content Scrambling System. It does not allow the DVD title content to be accessed without DeCSS. This work is only for research purposes and DVD movie contents are not stored after extracting the frame information.

According to the ISO/IEC 13818 [49], every frame header begins with a unique 32 bit start code. The starting point of each frame is distinguished with a unique four byte start code. It has 23 zero bits followed by 1 one bit and the next one byte expresses the particular start code type. The 'Start Code' 0000 0000 indicates the picture header(0100). The frame types are found at bits 3 to 5 of byte 5. As shown in Figure 5.1, the frame types are extracted from these three bits. For the MPEG-2 file, the I frame is followed by the sequence header(01B3) and group of picture (GOP) header(01B8). In addition, four bits are appended beginning at byte 7, bit 2 when the frame types indicate 010 (P frame) or 011 (B frame). Actually, this field is used for MPEG-1 so that MPEG-2 is set to 0111 for P, and B frame. Figure 5.1 shows the start code prefix.

Sometimes random hex codes are the same with a unique four byte start code. To verify whether the extracted frame is correct, the checks below are performed.

(a) Every frame should have slice numbered 1 to 30,

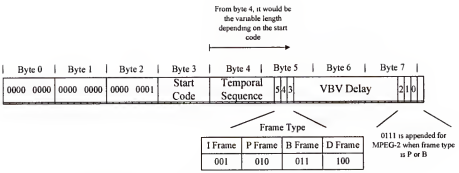

Figure 5.1: Start header for MPEG-2 video frame

(b) The specific byte should include 0111 for P and B frames, and

(c) The sequence header(01B3) and group of picture (GOP) header(01B8) are required to start the I frame.

The C program seeks each starting point of the video frame and calculates the distance between the starting points. The frame size is obtained from the distance between video starting codes. This program ignores the rest of the start codes because the sizes are small compared to the video frame. In Figure 5.1, the frame type also can be found by the next two bytes followed by the starting point of the video frame. Finally, it extracts every frame type and frame size in bytes.

5.2 DVD Characteristics

For the simulation, 37 different movies were chosen in studying DVD traffic characteristics. In this section, frame related information for several movies is presented. Table 5.1 shows information about the movies, such as the release date, rating, and genre. The release dates range from March, 1997 to May, 2004. These movie database includes 2 NR, 11PG, 9 PG-13, 12 R, and 3 G rated movies. Often, a movie does not have single genre. So, these movie database includes 4 Music and Performance, 12 Drama, 12 Sci-Fi and Fantasy, 5 Family and Kid, 13 Action and Adventure, 9 Comedy, and 2 Mystery and Suspense. Table 5.2 shows GOP related statistics including the most frequent GOP size, percentage of most frequent GOP size, maximum GOP size, and minimum GOP size. A GOP size of 12 is the most frequent in 34 of the 37 movies. The movie Deer Hunter and Passport to Paris have 15

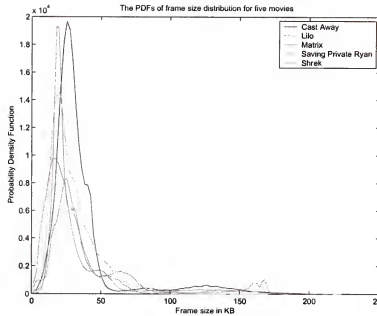

Figure 5.2: Statistics for movies

GOP size, and the movie 3 Tenors in concert 1994 has 18 GOP size as most frequent GOP. None of the movies exceed 18 as a maximum GOP size.

Table 5.3 shows the information for the movies, such as production studio, frames per sec, running time, and number of frames. The running time ranges from 85 minutes to 200 minutes and the average running time is 125.8 minutes. The total number of frames are ranged from 122670 to 327084 and the averaged total number of frames is 183117 per DVD movie.

5.3 Outline

In this chapter, we have shown DVD movie extraction and several movies' statistical characteristics. Actually, we thought that movie genre and DVD frame characteristics have some relationship, but there was no relationship between them. we thought there would be some relationship between movie genre and frame characteristics, but we found none. Movie characteristics depend on the production company, and movie running time. The production companies use different MPEG-2 encoder to make DVD titles and they use different compression techniques. We also present the statistical properties for each movie. The frame

information for various MPEG-2 movies is valuable because there is no known place to provide this information in public. It helps other researchers to use this data for developing MPEG traffic control on the network.

The next chapter describes new work on the key characteristics of DVD traffic to determine a DVD synthesis model.

Table 5.1: Information for 37 DVD movies

	Release date	Rating	Genre
3 Tenors in concert	07/02/1997	NR	Music&Performance
8mm	09/14/1999	R	Mystery &Suspense
A.I. (W)	03/05/2002	PG-13	Drama, Sci-Fi & Fantasy
Baby's Day Out	01/29/2002	PG	Comedy, Family &Kids
Baby's Day out (W)	01/29/2002	PG	Comedy, Family &Kids
Beautiful Mind	06/25/2002	PG-13	Drama
Before Sunrise	11/30/1999	R	Comedy, Drama, Romance
Before Sunrise (W)	11/30/1999	R	Comedy,Drama,Romance
Cast Away	06/12/2001	PG-13	Action, Adventure, Drama
Deer Hunter	03/31/1998	R	Drama, War
Hannibal	08/21/2001	R	Mystery, Suspense
Last Samurai	05/04/2004	R	Action, Adventure, Drama
Life is Beautiful	11/09/1999	PG-13	Comedy, Drama, War
Lilo & Stitch	12/03/2002	PG	Family &Kids, Comedy
Lord of the Ringl	08/06/2002	PG-13	Action, Adventure, Sci-Fi&Fantasy
Lord of the Ring II	11/18/2003	PG-13	Action, Adventure, Sci-Fi&Fantasy
Lord of the Ring III	05/25/2004	PG-13	Action, Adventure, Sci-Fi&Fantasy
Lovers on the Bridge	03/13/2001	R	Drama, Romance
Man in the Iron Mask	08/12/1998	PG-13	Action, Adventure,Drama
Matrix	09/21/1999	R	Action, Adventure, Sci-Fi &Fantasy
Matrix Reloaded	10/14/2003	R	Action, Adventure, Sci-Fi &Fantasy
Matrix Revolutions	04/06/2004	R	Action, Adventure, Sci-Fi &Fantasy
Passport to Paris	02/12/2002	G	Comedy, Family, Kids
Perfect Storm	11/14/2000	PG-13	Action, Adventure, Drama
Princess Caraboo	04/24/2001	PG	Comedy, Drama
Queen: We will Rock You	12/16/1997	NR	Music&Performance
Runaway Bride	01/25/2000	PG	Comedy, Romance
Saving Private Ryan	05/25/1999	R	Action, Drama, Period,War
Scooby Doo	10/11/2002	PG	Action, Adventure, Comedy, Family&Kids
Shrek	11/02/2001	PG	Family &Kid, Comedy, Sci-Fi &Fantasy
Sound of Music	08/13/2002	G	Drama, Music &Performance, Romance
Star Wars II	11/12/2002	PG	Action, Adventure, Sci-Fi& Fantasy
Mutant Ninja Turtle	02/24/1998	PG	Action&Adventure,Sci-Fi&Fantasy, Sports&Fitness
Mutant Ninja Turtle (W)	02/24/1998	PG	Action&Adventure,Sci-Fi&Fantasy, Sports&Fitness
Terminator3	11/11/2003	R	Action&Adventure, Sci-Fi&Fantasy
Wizard of OZ	03/26/1997	G	Family & Kid, Sci-Fi&Fantasy, Music&Performance
Xanadu (Widescreen)	07/20/1999	PG	Music&Performance,Sci-Fi&Fantasy

Table 5.2: GOP size statistics for 37 DVD movies

	Most frequent GOP	Percentage	Max GOP	Min GOP
3 Tenors in concert	18	97.82 %	18	2
8 mm	12	99.58 %	18	2
A.I.	12	99.22 %	16	1
Baby's Day Out	12	69.67 %	15	1
Baby's Day Out(W)	12	73.93 %	15	1
Beautiful Mind	12	99.65 %	18	1
Before Sunrise	12	99.80 %	12	1
Before Sunrise(W)	12	99.83 %	12	3
Cast Away	12	86.18%	14	1
Deer Hunter	15	78.97 %	18	1
Hannibal	12	69.92 %	14	1
Last Samurai	12	99.57 %	12	2
Life is Beautiful	12	83.72 %	14	4
Lilo & Stitch	12	63.11%	14	1
Lord of the Ring I	12	99.66 %	14	1
Lord of the Ring II	12	99.69 %	14	1
Lord of the Ring III	12	99.87 %	14	6
Lovers on the Bridge	12	99.70 %	15	5
Man in the Iron Mask	12	78.11 %	14	1
Matrix	12	99.59%	13	3
Matrix Reloaded	12	99.21 %	12	1
Matrix Revolutions	12	99.30 %	12	1
Passport to Paris	15	99.74 %	15	1
Perfect Storm	12	99.51 %	12	1
Princess Caraboo	12	99.55 %	15	4
Queen	12	96.44 %	12	3
Runaway Bride	12	79.85 %	15	1
Saving Private Ryan	12	89.44%	14	3
Scooby Doo	12	99.69%	12	2
Shrek	12	99.26%	18	1
Sound of Music	12	87.38%	15	1
Star Wars II	12	67.92%	14	1
Mutant Ninja Turtle	12	99.84%	12	1
Mutant Ninja Turtle(W)	12	99.84%	12	1
Terminator3	12	98.95%	18	4
Wizard of OZ	12	99.71%	13	1
Xanadu (W)	12	93.04%	15	1

Table 5.3: Statistics for 37 DVD movies I

	Company	fps	Run time	# of frames(size)
3 Tenors in concert	Wea/Atlantic	25	141 min	200470 (4.35GB)
8 mm	Columbia/Tristar	25	123 min	177409 (3.75GB)
A.I.	Universal	25	145 min	209910 (7.20GB)
Baby's Day Out	20th centry/Fox	25	99 min	142162 (3.56GB)
Baby's Day Out(W)	20th centry/Fox	25	99 min	142220 (3.57GB)
Beautiful Mind	Universal	25	136 min	194729 (6.49GB)
Before Sunrise	Castle Rock	25	101 min	145271 (4.13GB)
Before Sunrise(W)	Castle Rock	25	101 min	145201 (4.14GB)
Cast Away	Fox	25	143 min	206867 (7.02GB)
Deer Hunter	Universal	25	183 min	327084 (7.23GB)
Hannibal	MGM/UA	25	131 min	189213 (7.35GB)
Last Samurai	Warner Home	25	154 min	221770 (7.11GB)
Life is Beautiful	Miramax	25	116 min	169989 (5.55GB)
Lilo & Stitch	WaltDesney	25	85 min	122670 (3.65GB)
Lord of the Ring I	New Line Home	25	178 min	256614 (6.98GB)
Lord of the Ring II	New Line Home	25	179 min	258043 (7.09GB)
Lord of the Ring III	New Line Home	25	200 min	289092 (7.61GB)
Lovers on the Bridge	Buena Vista Home	25	125 min	181363 (6.21GB)
Man in the Iron Mask	MGM/UA	25	132 min	189741 (4.16GB)
Matrix	Warner	25	136 min	196160 (4.90GB)
Matrix Reloaded	Wraner	25	138 min	198944 (6.25GB)
Matrix Revolutions	Warner	25	129 min	185917 (5.70GB)
Passport to Paris	Warner	25	87 min	157193 (3.66GB)
Perfect Storm	Warner	25	129 min	186839 (6.32GB)
Princess Caraboo	Columbia/Tristar	25	97 min	139396 (3.86GB)
Queen	Pioneer	25	96 min	138894 (4.12GB)
Runaway Bride	Paramount	25	116 min	167365 (6.58GB)
Saving Private Ryan	Dreamworks	25	170 min	212796 (5.93GB)
Scooby Doo	Warner	25	86 min	124487 (4.48GB)
Shrek	Dreamworks	25	90 min	129783 (5.19GB)
Sound of Music	Fox Home	25	174 min	251152 (7.51GB)
Star Wars II	20th centry/Fox	25	142 min	205116 (6.72GB)
Mutant Ninja Turtle	New Line Home	25	95 min	135754 (3.91GB)
Mutant Ninja Turtle(W)	New Line Home	25	95 min	134543 (3.92GB)
Terminator3	Warner	25	110 min	156869 (6.01GB)
Wizard of OZ	Warner	25	101 min	146461 (3.54GB)
Xanadu (W)	Universal	25	93 min	137851 (3.68GB)
Average		25	125.8 min	183117 (5.39GB)

CHAPTER 6
MODELING AND SYNTHESIS

6.1 Literature Review

The MPEG traffic modeling may be classfied into two group. One is frame size modeling, and other is traffic correlation. The frame size model includes normal distribution [50], gamma distribution [51], log normal distribution [52], and so on. In addition, previous work does not use nonlinear least-square data fitting methods. It only applies the arithmetic mean and variance from MPEG-2 movie data to get the gamma parameters. The error results are compared to our model in Table 6.2.

MPEG source model of traffic correlation has been studied extensively. Approaches include the Histogram based model, AR model, Markov-chain model [53], self-similar, fractal models, and non-linear model [54]. The video traffic model can be further subdivided to two areas. One is short term correlation, and the other is long term correlation. Many previous techniques are well adapted to short term dependency, while a good model for long term dependency is still open. The length of MPEG video data for previous work was only 20 to 30 minutes. Practically, the length of a movie is one and half hours to three hours long, so that the previous modeling is not adequate. Long term dependency is still an active research area [55].

6.2 Traffic Modeling

In this chapter, we will describe the various statistical results for MPEG traffic, including

(a) mean value,

(b) variance,

(c) skewness, and

(d) kurtosis.

Casella & Berger [56] explain that "the mean is the average data point value within a data set and the variance is the sum of the squared deviations of n measurements from their mean

divided by $(n-1)$. Most often, the median is used as a measure of central tendency when data sets are skewed. The metric that indicates the degree of asymmetry is called skewness. Skewness often results in situations when a natural boundary is present. Normal distributions will have a skewness value of approximately zero. Kurtosis is a parameter that describes the shape of a random variable's probability distribution. Normal distributions have a kurtosis of 3 (irrespective of their mean or standard deviation). If a distribution's kurtosis is greater than 3, it is said to be leptokurtic. If its kurtosis is less than 3, it is said to be platykurtic. Leptokurtosis is associated with distributions that are simultaneously peaked and have fat tails. Platykurtosis is associated with distributions that are simultaneously less peaked and have thinner tails" .

Table 6.1 shows the basic statistical values of average, variance, skewness, kurtosis, and maximum frame size. The total average frame size is 31.9093 KB or the average transmission speed is 6.388Mbps when 25 fps is assumed. The variances of frame size are ranged from 1.15 $\times 10^8$ to 11.8 $\times 10^8$. The maximum frame sizes are ranged from 104 KB to 249 KB and the mean maximum frame size is 166 KB. For example, the movie 'Cast Away' needs to send an average of 22.8 KB per TDMA slot when TDMA has a 25msec slot interval. In other words, it can send the data which are 22.8 KB average in size, 40 times per second.

6.3 Traffic Synthesis

The compression pattern of most MPEG-2(DVD) traffic is IBBPBBPBBPBB for a size 12 GOP. Some of the DVD compression actually results in 15 GOP. But, the GOP size in an MPEG-2 file is variable. As shown in Figure 4.2, the frame sequence is not constant; the GOP compression pattern may change sometimes. In this test, traffic trace data from 37 different DVD movies were selected for the simulation test. When the DVD movie frame sizes were regenerated, the distribution of individual frame sizes were considered without regard for their correlative relationship to other frames in the sequence.

The gamma distribution has been suggested to model the individual MPEG frame [57]. Eq. (6.1) shows the gamma PDF.

Gamma PDF

$$f(x) = \frac{1}{b^a \Gamma(a)} x^{a-1} e^{\frac{x}{b}} \tag{6.1}$$

where

$$b = \frac{\sigma}{mean}, \quad \text{and} \quad a = \frac{mean}{b} \quad (mean = ab \quad \text{and} \quad \sigma = ab^2).$$

Here, parameter a is a shape parameter and b is a scale parameter. The exponential PDF is a special case of the gamma PDF when the parameter a is equal to 1.

As shown in Table 6.2, one gamma function modeling does not fit well the MPEG data. So, we propose a two gamma function applied to fit the MPEG traffic synthesis. This is shown in Eq. (6.2). The parameters for Eq. (6.2) were obtained by a nonlinear least square algorithm.

$$f(x) = \alpha \frac{1}{b^a \Gamma(a)} x^{a-1} e^{\frac{x}{b}} + (1-\alpha) \frac{1}{d^c \Gamma(c)} x^{c-1} e^{\frac{x}{d}} \tag{6.2}$$

The Cumulative Distribution Function (CDF) should go to 1 when $x = \infty$, and therefore in Eq. (6.2), the variable α is chosen as its weight for the gamma function and $(1-\alpha)$ is the weight for other gamma function. Three or more gamma function modeling could give more flexibility, but the simulation results show that a three gamma function does not always give better results than a two gamma function modeling. Therefore, we decided to use two gamma function modeling instead of higher order for the rest of the modeling study.

The nonlinear least-square data fitting problem is one of the most widely encountered unconstrained optimization problems. Furthermore, due to the special structure of the objective functions, it is worth studying the special algorithms for solving nonlinear least-squares data fitting problems [58] of this form.

$$\min_{\alpha,a,b,c,d} \{f(\alpha, a, b, c, d)\} = \sum_{i=1}^{n} (f(x_i) - y_i)^2 = \sum_{i=1}^{n} f_i(x)^2 \tag{6.3}$$

To solve this kind of data fitting problem, it is better to calculate the vector value functions rather than calculate $f(\alpha, a, b, c, d)$.

$$f(\alpha, a, b, c, d) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{bmatrix} \tag{6.4}$$

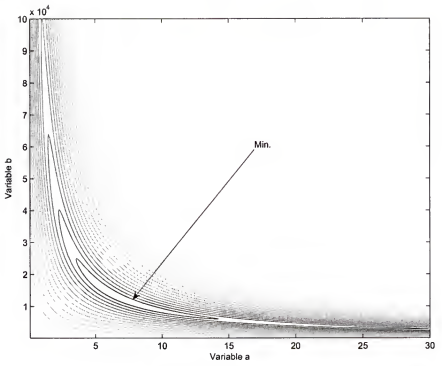

Figure 6.1: Global minimum for I frame

Then, in vector terms, this optimization problem may be restated as

$$\min_{x} \frac{1}{2}(|\ F(x)\ |)_2^2 = \frac{1}{2}\sum_i f_i(x)^2 \tag{6.5}$$

where x is a vector and F(x) is a function that returns a vector value. Figure 6.1 shows that the estimate we obtain from data fitting algorithm is the global minimum, not local minimum.

The Root Mean Square Error technique is used to check whether a two gamma function is better than one gamma function. The root mean square error in Eq. (6.6) is used as a global measure of error between the original value and estimated value.

$$Error = \sqrt{E[(Y - g(x))^2)]} \tag{6.6}$$

The results for the root mean square show that two gamma function modeling is better than one gamma function modeling.

The gamma function models for aggregate MPEG traffic did not fit well. After that, the gamma function was applied to the individual I, P, and B frame models. Eventually, individually fitted models for I, P, and B frame were better than all frames considered together.

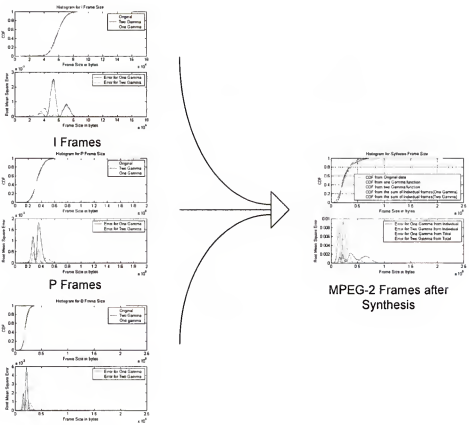

Figure 6.2: CDF of matrix DVD frame size modeling

After regenerating the I, P, and B frames, the results were combined to form MPEG-2 traffic according to in Eq. (6.7). Usually, a MPEG movie has 12 or 15 GOP size. If it has 12 GOP size, there is 1 I frame, 3 P frames, and 8 B frames. If it has 15 GOP size, there is 1 I frame, 4 P frames, and 10 B frames. Eq. (6.7) below shows the general GOP case.

$$f(x) = \frac{1}{N_T}[N_I \times f_I(x) + N_P \times f_P(x) + N_B \times f_B(x)] \tag{6.7}$$

where N_I = Number of I Frames, N_P = Number of P Frames, N_B = Number of B Frames, and N_T = Number of total Frames.

Figure 6.2 shows how frames are reproduced from the stored data. First, individual I, P, and B frames are generated using the gamma function. Then, with each individual frame, an MPEG-2 file is created.

Table 6.2 compares the RMS error of the one gamma modeling with I, P, and B frames together, the two gamma modeling with I, P, and B frame together, the one gamma modeling with I, P, and B frames individually, and the two gamma modeling with I, P, and B frame individually.

In the case of the one gamma distribution modeling with I, P, and B frame individually, there are two different methods. One is derived from nonlinear least-square data fitting methods, the other is based on the gamma probability density function with arithmetic mean and variance from the collected data.

6.4 Traffic Autocorrelation

Several different methods are proposed for MPEG traffic autocorrelation modeling and they are still controversial. Some methods are simple computationally, but fail to track the traffic characteristics. Others have good trace results, but only work for specific test models. Therefore, a review of several methods is presented in this section.

There are Markov chain models, AR processes, self-similar models, and nonlinear neural network models [59]. In addition, there are many papers that mix two methods.

The SRD (Short Range Dependency) characteristics of MPEG video data are captured easily with any method mentioned above because it does not involve any scene change. But, the LRD (Long Range Dependency) is an active research area. It includes scene changes. As an example to estimate the scene change point, Eq. (6.8) can be used with simple calculation. To calculate the long term dependency, the decision of scene change point is critical.

$$\frac{[X_I(n+1) - X_I(n)] - [X_I(n) - X_I(n-1)]}{(1/25)\sum_{j=n-24}^{n} X_I(j)} < -\lambda \tag{6.8}$$

The λ used by this model to choose the scene change point was 0.65 [60].

The typical AR model with a second order AR process can be implemented in Eq. (6.9) [55].

$$\delta = a_1\delta_I(n-1) + a_2\delta_I(n-2) + \epsilon(n) \tag{6.9}$$

Here, $\epsilon(n)$ is an i.i.d. random variable with zero mean value.

Usually, the self-similarity model refers to the LRD model. The parameter H is the hurst parameter given by $H = 1 - \beta/2$ and the value of H shows the tendency of dependency characteristics.

6.5 Outline

In this chapter, we present the two gamma distribution modeling with nonlinear least squares data fitting algorithm. Previous work uses arithmetic mean and variance of empirical MPEG movie data. We showed that our model is outperform the other works.

In the next chapter, we will show the bandwidth allocation scheme for DVD traffic in home networking.

Table 6.1: Statistics for 37 DVD movies II

	Average (KB/frame)	Variance	Skewness	kurtosis	Max
3 Tenors in concert	23.327 (4.67 Mbps)	1.92×10^8	2.5832	12.5275	145 KB
8 mm	22.751 (4.55 Mbps)	1.58×10^8	2.8860	18.0806	168 KB
A.I.	36.831 (7.37 Mbps)	5.98×10^8	1.8080	7.0586	189 KB
Baby's Day Out	26.927 (5.38 Mbps)	7.48×10^8	2.6108	9.7836	227 KB
Baby's Day Out(W)	27.009 (5.40 Mbps)	3.97×10^8	2.2788	8.3507	185 KB
Beautiful Mind	35.820 (7.16 Mbps)	8.08×10^8	2.4900	9.9186	184 KB
Before Sunrise	30.571 (6.11 Mbps)	3.24×10^8	1.6674	5.8194	145 KB
Before Sunrise(W)	30.632 (6.12 Mbps)	3.30×10^8	1.6636	5.8408	156 KB
Cast Away	36.483 (7.30 Mbps)	8.42×10^8	2.8847	11.4541	217 KB
Deer Hunter	23.739 (4.75 Mbps)	1.15×10^8	2.3677	9.5856	104 KB
Hannibal	41.739 (8.35 Mbps)	1.18×10^9	2.9133	10.9259	249 KB
Last Samurai	34.466 (6.89 Mbps)	1.62×10^8	1.5542	6.4532	139 KB
Life is Beautiful	35.063 (7.01 Mbps)	8.76×10^8	2.7079	9.7276	181 KB
Lilo & Stitch	31.996 (6.34 Mbps)	1.04×10^9	2.5574	9.7077	247 KB
Lord of the Ring I	29.236 (5.85 Mbps)	4.18×10^8	1.8012	6.5578	138 KB
Lord of the Ring II	29.532 (5.91 Mbps)	4.31×10^8	1.9033	8.4501	166 KB
Lord of the Ring III	28.301 (5.66 Mbps)	3.76×10^8	1.5467	5.8047	136 KB
Lovers on the Bridge	36.775 (7.36 Mbps)	9.76×10^8	2.4524	8.5812	157 KB
Man in the Iron Mask	23.571 (4.71 Mbps)	2.59×10^8	2.0787	7.3452	134 KB
Matrix	26.839 (5.37 Mbps)	1.75×10^8	1.5443	5.2929	141 KB
Matrix Reloaded	33.752 (6.75 Mbps)	2.01×10^8	1.9178	10.4456	172 KB
Matrix Revolutions	32.977 (6.60 Mbps)	1.43×10^8	1.2758	5.4484	119 KB
Passport to Paris	25.040 (5.01 Mbps)	1.97×10^8	1.4799	5.1594	126 KB
Perfect Storm	36.362 (7.27 Mbps)	1.57×10^8	0.9430	4.0535	138 KB
Princess Caraboo	29.749 (5.95 Mbps)	3.16×10^8	2.4303	10.7326	164 KB
Queen	31.898 (6.38 Mbps)	3.33×10^8	1.0153	3.9885	127 KB
Runaway Bride	42.266 (8.45 Mbps)	9.65×10^8	2.6700	9.6056	202 KB
Saving Private Ryan	29.934 (5.99 Mbps)	2.80×10^8	1.5936	6.3956	171 KB
Scooby Doo	38.659 (7.73 Mbps)	1.87×10^8	1.5065	6.0723	137 KB
Shrek	42.948 (8.59 Mbps)	1.34×10^9	2.1260	7.1102	186 KB
Sound of Music	32.120 (6.42 Mbps)	8.77×10^8	2.7118	9.9696	193 KB
Star Wars II	35.205 (7.04 Mbps)	4.87×10^8	2.2025	8.5485	228 KB
Mutant Ninja Turtle	30.966 (6.19 Mbps)	1.25×10^8	1.7694	7.6534	148 KB
Mutant Ninja Turtle(W)	31.296 (6.26 Mbps)	1.22×10^8	1.7799	7.8743	140 KB
Terminator3	41.178 (8.24 Mbps)	8.31×10^8	2.5094	9.5070	191 KB
Wizard of OZ	25.976 (5.20 Mbps)	2.05×10^8	1.6677	5.5619	143 KB
Xanadu (W)	28.710 (5.74 Mbps)	4.62×10^8	2.1596	9.2138	175 KB
(Average)	31.909 (6.38 Mbps)	4.44×10^8	2.0556	8.2325	166 KB

Table 6.2: Root mean square errors

	Two gamma w/ total	One gamma w/ others	One gamma w/ individual	Two gamma w/ individual
3 Tenors in concert	0.0098	0.0072	0.0074	0.0024
8 mm	0.0087	0.0022	0.0034	0.0022
A.I.	0.0203	0.0206	0.0145	0.0145
Baby's Day Out	0.0413	0.0046	0.0038	0.0038
Baby's Day Out(W)	0.0203	0.0050	0.0036	0.0023
Beautiful Mind	0.0367	0.0102	0.0082	0.0082
Before Sunrise	0.0238	0.0212	0.0035	0.0018
Before Sunrise(W)	0.0219	0.0412	0.0029	0.0021
Cast Away	0.0326	0.0058	0.0048	0.0030
Deer Hunter	0.0248	0.0056	0.0031	0.0023
Hannibal	0.0390	0.0045	0.0038	0.0024
Last Samurai	0.0158	0.0064	0.0057	0.0039
Life is Beautiful	0.0416	0.0107	0.0074	0.0057
Lilo & Stitch	0.0281	0.0087	0.0078	0.0078
Lord of the Ring I	0.0197	0.0100	0.0096	0.0045
Lord of the Ring II	0.0098	0.0075	0.0055	0.0052
Lord of the Ring III	0.0112	0.0097	0.0073	0.0071
Lovers on the Bridge	0.0402	0.0077	0.0062	0.0054
Man in the Iron Mask	0.0291	0.0080	0.0049	0.0046
Matrix	0.0221	0.0191	0.0057	0.0037
Matrix Reloaded	0.0175	0.0072	0.0061	0.0050
Matrix Revolutions	0.0155	0.0187	0.0091	0.0066
Passport to Paris	0.0249	0.0067	0.0047	0.0017
Perfect Storm	0.0075	0.0237	0.0027	0.0027
Princess Caraboo	0.0223	0.0025	0.0026	0.0022
Queen	0.0098	0.0142	0.0126	0.0031
Runaway Bride	0.0406	0.0084	0.0070	0.0045
Saving Private Ryan	0.0123	0.0046	0.0024	0.0024
Scooby Doo	0.0203	0.0066	0.0034	0.0030
Shrek	0.0355	0.0123	0.0098	0.0078
Sound of Music	0.0388	0.0084	0.0066	0.0026
Star Wars II	0.0219	0.0034	0.0028	0.0027
Ninja Turtle	0.0235	0.0304	0.0039	0.0021
Ninja Turtle(W)	0.0160	0.0056	0.0038	0.0032
Terminator3	0.0351	0.0071	0.0041	0.0029
Wizard of OZ	0.0275	0.0437	0.0055	0.0019
Xanadu (W)	0.0121	0.0050	0.0034	0.0034

CHAPTER 7
BANDWIDTH ALLOCATION SCHEME

7.1 Literature Review

The bandwidth allocation scheme for CBR MPEG video traffic is very easy since the bit rate does not change much. But MPEG-2 based DVD commercial movies are VBR video. To deliver the VBR MPEG file without loss, the peak data rate can be used as the entire bandwidth assignment. It is simple, but it wastes available network resource. In 1996, John Lauderdale proposed the Pre-encoded VBR MPEG video using CBR service, which claimed that the "minimum reservation rate" is much lower than the peak rate [61]. Nonetheless minimum reservation rate, does not provide the higher bandwidth utilization. The other research for bandwidth smoothing technique for stored video was done by Wu-chi Feng and Jennifer Rexford [62]. This bandwidth smoothing technique computes a transmission schedule for stored video or video on demand. The primary goal of this technique is reducing the peak transmission rate. These approaches need pre-recorded video, not real time video. Their work has been extended to live video smoothing, but it requires several seconds to a minute of delay [63]. The bandwidth smoothing technique has been studied by several authors. In [64], the minimization for the number of bandwidth rate increased requirement was considered. In [65], minimization for the buffer utilization of the client buffer was considered and in [66], delivery video in constant bandwidth allocation period was studied.

7.2 TDMA Scenario

TDMA transmission traditionally assigns a fixed bandwidth. To accommodate multimedia delivery with a fixed bandwidth allocation, more bandwidth is needed. As shown in Figure 7.1, the average peak-to-mean ratio is at least 2. This means that the bandwidth assignment should be twice the average bandwidth using the peak rate bandwidth scheme. Even if the minimum reservation rate is used, an assigned bandwidth larger than 150% of the

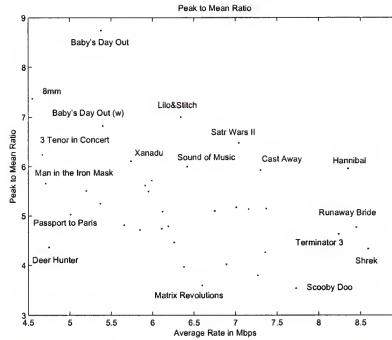

Figure 7.1: Peak to mean ratio of data rate

average bandwidth is needed, which is shown in Table 7.1 and Figure 7.2 for zero underflow. Underflow occurs when the frame is not delivered to the receiver on time.

In Table 7.1, the peak data rate is calculated from $\frac{Maximum\ Frame\ Size}{Frame\ Period}$, and the max. of 1 sec avg. is

$$R = \max_{1 \le k \le m-24} \frac{Fr_k + Fr_{k+1} + \cdots + Fr_{k+24}}{T_k + T_{k+1} + \cdots + T_{k+24}} \tag{7.1}$$

where $Fr_k + Fr_{k+1} + \cdots + Fr_{k+24}$ is the sum of frame sizes for one second, $T_k + T_{k+1} + \cdots + T_{k+24}$ is the frame period which is equal to 1 second, and m is number of frames.

Our purpose is to reduce the wasted bandwidth while minimizing jitter. According to our simulation, we can reduce the bandwidth from 115% to 101% without a drop in performance.

The scenario to be simulated is shown in Figure 7.3. The frames generated from the MPEG-2 source (which are collected by the above C program) are inserted into the smoothing buffer at the frame rate (25fps). The frame rate of 37 collected movies is 25fps, as shown in Table 5.3. Data in the smoothing buffer is served by a periodic TDMA session with a given period and bandwidth and inserted in the MAC receive buffer. The frames from the MAC

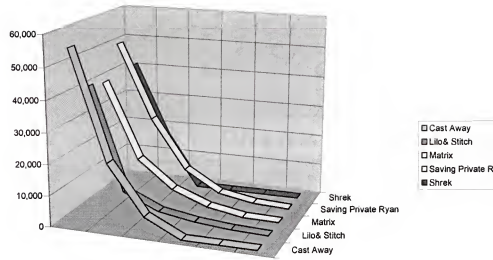

Figure 7.2: Fixed bandwidth allocation results

receive buffer are drained at a fixed rate by the MPEG-2 sink. Details of each of the entities and statistics are presented in Table 7.2.

Bandwidth channel allocation is modelled as a periodic Distributed-TDMA session of a certain period and bandwidth. Each of the combinations of the following values were simulated.

Smoothing buffer and MAC Receive Buffer is considered to be infinitely large. One of the major goals of this simulation was to obtain the probability density distribution of the buffer occupancy to estimate the necessary buffer size. This distribution was obtained by sampling the buffer at small intervals (1 msec).

The MPEG-2 sink drains the frames at the same rate that they are generated (and also the same order). Obtaining the optimal time at which the sink starts draining the packets is one of the parameters that we want to estimate. This interval could be 300msec, 400msec, 500 msec. Another parameter of interest is the buffer underflow statistics to check how many frames are not delivered on time.

The initial bandwidth assigned is an important parameter. It takes long time to track the variation of required bandwidth with small value of initial bandwidth. The large value of initial bandwidth requires less time to track the variation, but a large value of initial bandwidth needs larger assigned bandwidth. Therefore, the optimal point of initial value is essential.

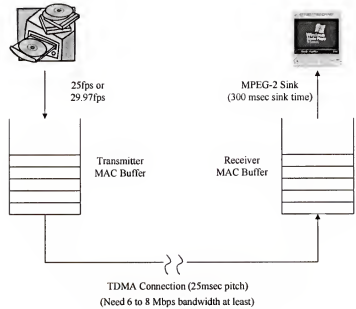

Figure 7.3: Scenario for MPEG-2 traffic transmission through TDMA

7.3 Bandwidth Allocation Scheme

In this section, our proposed bandwidth allocation strategy is described. By nature, MPEG-2 files rapidly change their required bandwidth, so extra wasted bandwidth is inevitable with any static bandwidth allocation. The MPEG-2 file generates new frames either every 1/25 second or 1/29.97 second according to the MPEG-2 header information. NTSC uses 29.97fps and PAL uses 25fps. The generated frames have various sizes and it is not easy to predict the required bandwidth without parsing the MPEG-2 file in advance. Several bandwidth smoothing algorithms have been proposed over the past decade. Earlier work relates to reducing the burstiness of bandwidth variations and requires frame size information in advance to calculate the transmission schedule to minimize the bandwidth variation [7, 8]. We have developed a new method to estimate the required bandwidth using transmit buffer size variations, and without any frame size information.

First, the simulation starts with fixed bandwidth allocation throughout the entire movie. In this case, much bandwidth was wasted to provide the QoS. The purpose of this simulation is to present this as a reference model and to compare it with our new strategy.

Bandwidth allocation is accomplished by the variation of the buffer size. The amount of allocated bandwidth is determined by the difference between the smoothed buffer size

and current buffer size. To avoid a sudden change of bandwidth allocation, the smoothed bandwidth size is also maintained. Here, the smoothed value means that it averages the whole value so far. The smoothed buffer size and smoothed bandwidth are obtained by Eq. 7.2 to Eq. 7.5

$$S_{Avg\_bu} = \alpha \times S_{Avg\_bu} + (1 - \alpha) S_{bu\_Hist} \tag{7.2}$$

In Eq. (7.2), the average buffer size is updated with smoothing calculation. Here, S_{Avg_bu} is average buffer size with smoothed calculation and S_{bu_Hist} is average buffer size from recent buffer history. The variable α is the smoothing factor. The initial value of S_{Avg_bu} is 2500 bytes, which means that 2500 byte x 8 bit/Byte x 40 TDMA pitch / sec = 800 kbps is the initial bandwidth size.

$$Slopes = \overline{TxBufferHist} - S_{Avg\_bu} \tag{7.3}$$

Eq. (7.3) checks the variance between recent buffer size and accumulated buffer size. The magnitude indicates how steep it is. To prevent rapid changes of bandwidth allocation, the variable *Slopes* can not be greater than 10 x S_{Avg_bu}.

$$BW_{Curr} = BW_{Avg} + Slopes/\gamma \tag{7.4}$$

With the calculated slopes, the BW_{Curr} updates the bandwidth according to the variation of buffer size in Eq. (7.4).

$$BW_{Avg} = \beta \times BW_{Avg} + (1 - \beta) BW_{curr} \tag{7.5}$$

Eq. (7.5) updates the cumulative bandwidth allocation with a smoothing calculation. Otherwise, the bandwidth change would fluctuate. It would cause overflow and underflow at the receiver buffer side. To keep a certain amount of bandwidth assignment, a smoothing technique is used. If the smoothing factor β is small, bandwidth can be updated quickly. Figure 7.4 shows how it calculates the bandwidth allocation every 500msec.

As shown in Figure 7.5 and Figure 7.6, the simulation was conducted for various combination of the parameters α, β, and γ. These yielded 192 simulations for each movie data set

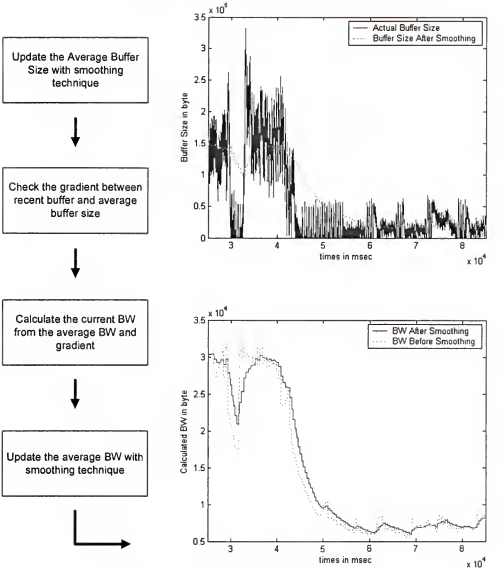
Update the Average Buffer Size with smoothing technique
Check the gradient between recent buffer and average buffer size
Calculate the current BW from the average BW and gradient
Update the average BW with smoothing technique
x 10^5
Actual Buffer Size
Buffer Size After Smoothing
Buffer Size in byte
times in msec
x 10^4
x 10^4
BW After Smoothing
BW Before Smoothing
Calculated BW in byte
times in msec
x 10^4

Figure 7.4: Bandwidth allocation scheme

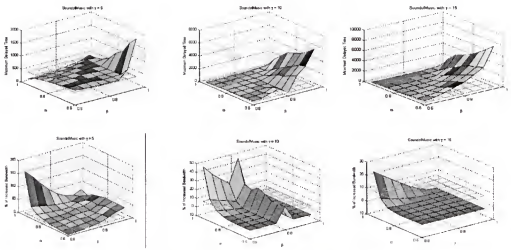

Figure 7.5: Choosing parameters

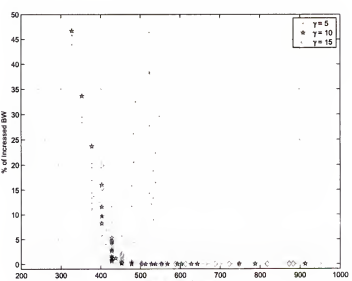

Figure 7.6: Relationship between delay time and assigned bandwidth for different α, β, and γ (3 tenors in concert 1994)

as shown in Table 7.3. When the γ value is small, the variation of the assigned bandwidth fluctuates because it is the weighting value for bandwidth calculation. When the α value is larger, the assigned bandwidth is increased while the number of underflows is reduced. New average buffer size value calculations need to reflect the buffer size variation slowly because the weighting value of cumulated average buffer size is 0.94 and recent buffer size is only 0.06. When the β value is larger, the assigned bandwidth is decreased while the number of underflows is increased. New bandwidth value calculation needs to reflect the buffer size variation quickly because the weighting value of cumulated average assigned bandwidth is 0.87 and recent buffer size is only 0.13. The best combination of values for parameters α, β, and γ were obtained for each movie from extensive simulations. Although the each of 37 movies have their own optimal value combination of parameters α, β, and γ, parameter values we assigned $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$ showed excellent results for all 37 movies. The values α and β are the empirical values and affect the smoothed averages. According to the values α and β, the assigned bandwidth goes high while the successful frame transfer rate goes down, and vice versa. In addition, we maintained 5 recent transmitter buffer histories to trace the changing of the buffer. The 5 recent transmitter buffer histories are compared to the cumulative transmitter buffer size. thus, the system could determine if it needs to increase or decrease the current allotted slot time.

Table 7.6 shows required bandwidth and delay time for $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$ with 20 ms processing time and Table 7.7 shows required bandwidth and delay time for $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$ with 40 ms processing time. The processing time refers to the difference between the time that updates new required bandwidth and the time that applies to transmission. The increased processing time induces the increased assigned bandwidth and longer delay time, but the increment is not significant.

Table 7.8 shows number of underflows with various buffering times for $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$. The number of underflow is increased when the buffering time at receiver side is shorter than 500 ms. In this simulation, we chose 300 ms, 350 ms, 400 ms, and 450 ms buffering time. The number of underflow ranges from 7 to 1227.

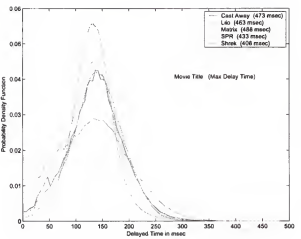

Figure 7.7: Delayed time statistics

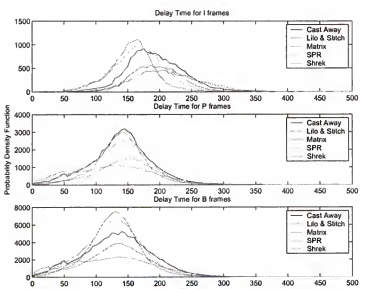

Figure 7.8: Delayed time statistics for individual frame

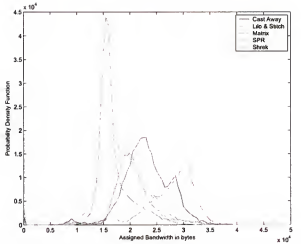

Figure 7.9: PDF of assigned bandwidth in every 500msec

7.4 Results

Figure 7.7 shows delay time statistics for entire movies and Figure 7.8 shows the delay time statistics for individual I, P, and B frames. The delay time refers to the difference between the frame generation time and arrival time at the receiver buffer. All delay times are less than 500msec. According to this result, we decided that the receiver drain time is 500 msec. Otherwise, there is underflow at the receiver buffer side.

Figure 7.9 shows the assigned bandwidth statistics. The average assigned bandwidth values were around 20 to 25 KB / pitch time and most of assigned bandwidth were lower than 40 KB / pitch time.

Figure 7.10 shows underflow statistics at receiver side when different bandwidth updating times are chosen. The bandwidth updating time is the most critical part because frequent bandwidth updating results in heavy traffic loads on the network, while less frequent updating time results in bad adaptation for the multimedia traffic. As shown in Figure 7.10, the percentage of increased bandwidth and the number of underflow frames are increased when bandwidth updating time is increased. In addition, larger bandwidth updating time results in a larger delay time. This is shown in Figure 7.11. The larger delay time causes a larger receiver buffer drain time. Therefore, we chose the 500msec bandwidth updating time for the optimal result.

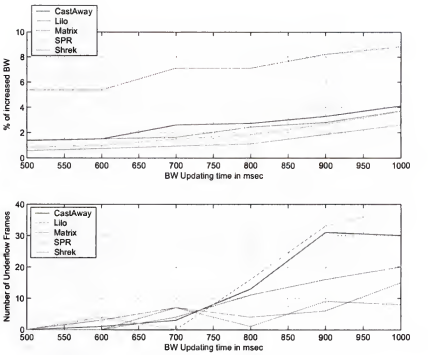

Figure 7.10: Bandwidth update time statistics

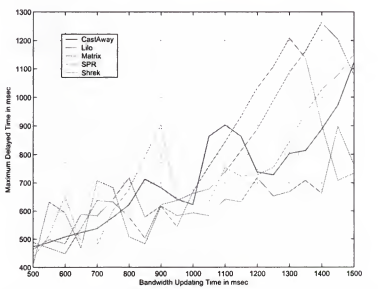

Figure 7.11: Maximum delay time statistics with different bandwidth update time

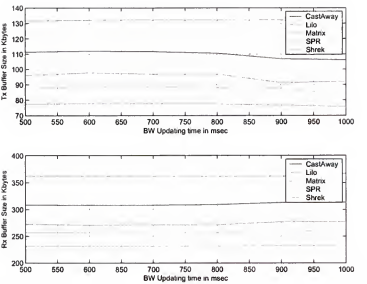

Figure 7.12: Buffer size statistics vs. bandwidth update time

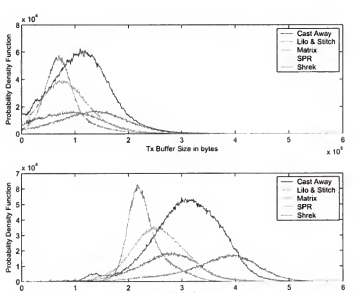

Figure 7.13: PDF of Tx and Rx buffer size

In Figure 7.12, the relationship between the buffer size and bandwidth updating time is shown. The transmitter buffer size reaches small values while bandwidth updating time goes to larger values. These changes do not affect the buffer size statistics.

Finally, we have several critical values for calculating the bandwidth allocation. As mentioned above, $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$. The bandwidth allocation updating time is 500msec, the receiver drain time(buffering time) at the receiver side is 500msec. The buffer history at the transmitter has 5 recent buffer sizes. If we use a large buffer history, it causes a slow response time while a small buffer history makes an unstable system because average over the buffer history fluctuates too much.

Figure 7.13 shows the buffer occupancy of the transmit and receiver buffers. The receiver buffer holds the frames for extra buffering time. As a result, the receiver buffer has higher occupancy than the transmit buffer.

Eventually, the results show that proposed bandwidth allocation scheme reduces the assigned bandwidth to less than 10% of the average bandwidth and has delay time less than 500 msec from the transmission side buffer to receiver side buffer at a bandwidth updating time of 500 msec.

7.5 Outline

In this chapter, we proposed the new technique to assign the bandwidth for aggregated MPEG movie. The proposed bandwidth allocation scheme uses current buffer size information from MAC layer. It does not need frame information, others requires the frame information before assigning the bandwidth. It also reduce the assigned bandwidth, lower the delay time, and maintain the small buffer size.

Table 7.1: Required bandwidth for several bandwidth assignment methods

	Proposed scheme	Minimum reservation rate	Max. of 1 sec avg.	Peak data rate
3 Tenors in concert	1.07%	52 %	70 %	524 %
8mm	1.81%	104 %	138 %	637 %
A.I. (W)	1.90%	43 %	58 %	415 %
Baby's Day Out	11.92%	80 %	102 %	774 %
Baby's Day out (W)	4.53%	58 %	95 %	583 %
Beautiful Mind	2.60%	35 %	57 %	414 %
Before Sunrise	0.55%	35 %	51 %	374 %
Before Sunrise (W)	0.58%	33 %	54 %	409 %
Cast Away	2.57%	26 %	50 %	493 %
Dear Hunter	1.75%	61 %	81 %	336 %
Hannibal	2.11%	21 %	41 %	496 %
Last Samurai	0.31%	29 %	50 %	302 %
Life is Beautiful	4.09%	29 %	46 %	417%
Lilo & Stitch	6.99%	45 %	76 %	600 %
Lord of the Ring I	4.90%	55 %	92 %	371 %
Lord of the Ring II	3.24%	62 %	98 %	462 %
Lord of the Ring III	3.97%	62 %	99 %	381 %
Lovers on the Bridge	2.44%	23 %	40 %	326 %
Man in the Iron Mask	3.53%	99 %	129 %	466 %
Matrix	0.76%	42 %	73 %	425 %
Matrix Reloaded	0.43%	31 %	50 %	410 %
Matrix Revolutions	0.55%	32 %	52 %	260 %
Passport to Paris	1.00%	37 %	66 %	403 %
Perfect Storm	0.24%	25 %	45 %	280 %
Princess Caraboo	0.98%	63 %	87 %	450 %
Queen	1.42%	38 %	54 %	297 %
Runaway Bride	2.22%	17 %	30 %	377 %
Saving Private Ryan	1.23%	59 %	92 %	472 %
Scooby Doo	0.25%	18 %	36 %	254 %
Shrek	2.30%	15 %	29 %	333 %
Sound of Music	4.74%	48 %	68 %	500 %
Star Wars II	1.77%	39 %	68 %	548 %
Mutant Ninja Turtle	0.28%	26 %	51 %	379 %
Mutant Ninja Turtle (W)	0.25%	28 %	53 %	346 %
Terminator3	1.20%	16 %	34 %	363 %
Wizard of OZ	0.38%	55 %	79 %	451 %
Xanadu (Widescreen)	3.15 %	68 %	94 %	511 %

Table 7.2: Important parameters for simulation

	parameters
TDMA Interval	25msec
Bandwidth Allocation Updating Time	500msec, 750msec,1000msec, 1500msec
Receiver Drain Start Time	300msec, 400msec, 500msec
Initial Cumulated Bandwidth	2500Bytes, 5000Bytes, 7500Bytes
Buffer History at Transmitter	Last 5 History, Last 10 History
Initial Bandwith	0.8Mbps, 1.6Mbps, 2.4Mbps

Table 7.3: Combination of conducted simulation parameters

	Values
α	0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, and 0.95
β	0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, and 0.95
γ	5, 10, and 15

Table 7.4: Required bandwidth with zero underflow for $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$

	% of increased bandwidth	Assigned bandwidth (original)
3 Tenors in concert 1994	1.07%	4.71Mbps(4.66Mbps)
8mm	1.81%	4.63Mbps(4.55Mbps)
A.I. (Widescreen)	1.90%	7.50Mbps(7.36Mbps)
Baby's Day Out	11.92%	6.02Mbps(5.38Mbps)
Baby's Day out (W)	4.53%	5.64Mbps(5.40Mbps)
Beautiful Mind	2.60%	7.35Mbps(7.16Mbps)
Before Sunrise	0.55%	6.14Mbps(6.11Mbps)
Before Sunrise (W)	0.58%	6.16Mbps(6.12Mbps)
Cast Away	2.57%	7.48Mbps(7.30Mbps)
Dear Hunter	1.75%	4.83Mbps(4.74Mbps)
Hannibal	2.11%	8.52Mbps(8.34Mbps)
Last Samurai	0.31%	6.91Mbps(6.89Mbps)
Life is Beautiful	4.09%	7.30Mbps(7.01Mbps)
Lilo & Stitch	6.99%	6.84Mbps(6.34Mbps)
Lord of the Ring I	4.90%	6.13Mbps(5.84Mbps)
Lord of the Ring II	3.24%	6.09Mbps(5.90Mbps)
Lord of the Ring III	3.97%	5.88Mbps(5.66Mbps)
Lovers on the Bridge	2.44%	7.53Mbps(7.35Mbps)
Man in the Iron Mask	3.53%	4.88Mbps(4.71Mbps)
Matrix	0.76%	5.40Mbps(5.37Mbps)
Matrix Reloaded	0.43%	6.78Mbps(6.75Mbps)
Matrix Revolutions	0.55%	6.63Mbps(6.59Mbps)
Passport to Paris	1.00%	5.05Mbps(5.00Mbps)
Perfect Storm	0.24%	7.29Mbps(7.27Mbps)
Princess Caraboo	0.98%	6.00Mbps(5.95Mbps)
Queen	1.42%	6.47Mbps(6.37Mbps)
Runaway Bride	2.22%	8.64Mbps(8.45Mbps)
Saving Private Ryan	1.23%	6.06Mbps(5.99Mbps)
Scooby Doo	0.25%	7.75Mbps(7.73Mbps)
Shrek	2.30%	8.78Mbps(8.59Mbps)
Sound of Music	4.74%	6.72Mbps(6.42Mbps)
Star Wars II	1.77%	7.16Mbps(7.04Mbps)
Mutant Ninja Turtle	0.28%	6.21Mbps(6.19Mbps)
Mutant Ninja Turtle (W)	0.25%	6.27Mbps(6.25Mbps)
Terminator3	1.20%	8.33Mbps(8.23Mbps)
Wizard of OZ	0.38%	5.21Mbps(5.19Mbps)
Xanadu (Widescreen)	3.15%	5.92Mbps(5.74Mbps)

Table 7.5: Required buffer size and delay time with $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$

	Avg. Tx buffer size in KB(max)	Avg. Rx buffer size in KB(max)	Avg. delay time in msec(max)
3 Tenors in concert	52.85 (246.86)	215.41 (445.23)	107 (373)
8mm	51.18 (554.88)	210.46 (548.89)	103 (428)
A.I. (W)	99.19 (496.50)	324.37 (604.55)	123 (498)
Baby's Day Out	60.16 (493.25)	249.51 (578.70)	97 (498)
Baby's Day out (W)	66.86 (392.43)	243.75 (589.30)	111 (443)
Beautiful Mind	94.67 (474.44)	317.26 (626.84)	120 (463)
Before Sunrise	78.81 (357.62)	272.78 (470.88)	120 (353)
Before Sunrise (W)	79.06 (391.37)	273.23 (483.27)	120 (398)
Cast Away	98.12 (487.33)	321.44 (605.48)	123 (418)
Dear Hunter	49.51 (270.76)	223.48 (438.40)	99 (483)
Hannibal	113.58 (647.23)	366.43 (697.93)	125 (418)
Last Samurai	87.84 (441.45)	308.52 (541.04)	119 (373)
Life is Beautiful	85.50 (381.40)	317.75 (546.45)	111 (398)
Lilo & Stitch	85.91 (522.56)	282.04 (571.44)	120 (463)
Lord of the Ring I	64.01 (480.46)	272.20 (554.65)	99 (373)
Lord of the Ring II	73.61 (475.93)	266.01 (594.39)	111 (453)
Lord of the Ring III	68.95 (475.38)	256.50 (554.74)	109 (388)
Lovers on the Bridge	98.63 (467.56)	324.27 (569.36)	123 (418)
Man in the Iron Mask	57.93 (512.02)	213.14 (536.26)	112 (438)
Matrix	67.49 (396.53)	241.18 (468.28)	117 (423)
Matrix Reloaded	86.41 (441.80)	301.76 (560.04)	119 (378)
Matrix Revolutions	83.83 (553.89)	295.41 (578.90)	119 (403)
Passport to Paris	62.25 (426.11)	225.71 (429.14)	116 (428)
Perfect Storm	92.81 (429.52)	325.36 (553.80)	120 (328)
Princess Caraboo	75.46 (376.96)	266.66 (553.86)	116 (493)
Queen	82.74 (343.98)	284.11 (503.01)	116 (323)
Runaway Bride	115.64 (458.23)	370.41 (609.56)	125 (413)
Saving Private Ryan	76.82 (469.23)	267.42 (551.37)	117 (398)
Scooby Doo	100.01 (438.72)	344.60 (569.71)	121 (378)
Shrek	116.90 (486.16)	377.00 (656.61)	124 (403)
Sound of Music	85.69 (513.02)	283.69 (562.14)	120 (458)
Star Wars II	93.83 (513.40)	311.02 (586.61)	121 (383)
Mutant Ninja Turtle	79.42 (310.88)	276.70 (457.86)	120 (443)
Mutant Ninja Turtle (W)	80.45 (356.32)	279.47 (480.30)	121 (443)
Terminator3	109.12 (559.99)	364.45 (605.67)	123 (483)
Wizard of OZ	64.12 (331.40)	234.60 (454.79)	116 (353)
Xanadu (Widescreen)	74.22 (582.32)	255.96 (581.89)	115 (403)

Table 7.6: Required bandwidth and delay time for $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$ (Processing time = 20 msec)

	% of increased bandwidth	Maximum delay time
3 Tenors in concert 1994	1.25%	373 msec
8mm	1.89%	428 msec
A.I. (Widescreen)	1.93%	498 msec
Baby's Day Out	11.96%	498 msec
Baby's Day out (W)	4.55%	443 msec
Beautiful Mind	2.63%	463 msec
Before Sunrise	0.55%	368 msec
Before Sunrise (W)	0.58%	398 msec
Cast Away	2.58%	443 msec
Dear Hunter	1.76%	483 msec
Hannibal	2.10%	418 msec
Last Samurai	0.32%	373 msec
Life is Beautiful	4.10%	408 msec
Lilo & Stitch	7.02%	463 msec
Lord of the Ring I	4.96%	388 msec
Lord of the Ring II	3.30%	478 msec
Lord of the Ring III	4.04%	408 msec
Lovers on the Bridge	2.45%	428 msec
Man in the Iron Mask	3.56%	438 msec
Matrix	0.78%	443 msec
Matrix Reloaded	0.44%	403 msec
Matrix Revolutions	0.56%	428 msec
Passport to Paris	1.01%	428 msec
Perfect Storm	0.24%	353 msec
Princess Caraboo	1.05%	493 msec
Queen	1.45%	333 msec
Runaway Bride	2.21%	438 msec
Saving Private Ryan	1.27%	423 msec
Scooby Doo	0.25%	383 msec
Shrek	2.31%	428 msec
Sound of Music	4.77%	458 msec
Star Wars II	1.78%	408 msec
Mutant Ninja Turtle	0.29%	443 msec
Mutant Ninja Turtle (W)	0.25%	443 msec
Terminator3	1.20%	483 msec
Wizard of OZ	0.38%	378 msec
Xanadu (Widescreen)	3.23%	413 msec

Table 7.7: Required bandwidth and delay time for $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$ (Processing time = 40 msec)

	% of increased bandwidth	Maximum delay time
3 Tenors in concert 1994	1.50%	383 msec
8mm	2.01%	453 msec
A.I. (Widescreen)	1.98%	498 msec
Baby's Day Out	12.00%	508 msec
Baby's Day out (W)	4.60%	448 msec
Beautiful Mind	2.69%	488 msec
Before Sunrise	0.58%	378 msec
Before Sunrise (W)	0.60%	423 msec
Cast Away	2.60%	443 msec
Dear Hunter	1.78%	483 msec
Hannibal	2.13%	418 msec
Last Samurai	0.35%	383 msec
Life is Beautiful	4.13%	423 msec
Lilo & Stitch	7.06%	463 msec
Lord of the Ring I	5.04%	388 msec
Lord of the Ring II	3.39%	478 msec
Lord of the Ring III	4.13%	408 msec
Lovers on the Bridge	2.48%	438 msec
Man in the Iron Mask	3.62%	443 msec
Matrix	0.82%	443 msec
Matrix Reloaded	0.47%	403 msec
Matrix Revolutions	0.60%	428 msec
Passport to Paris	1.04%	428 msec
Perfect Storm	0.27%	363 msec
Princess Caraboo	1.15%	518 msec
Queen	1.52%	343 msec
Runaway Bride	2.23%	438 msec
Saving Private Ryan	1.33%	448 msec
Scooby Doo	0.26%	408 msec
Shrek	2.36%	428 msec
Sound of Music	4.82%	458 msec
Star Wars II	1.83%	408 msec
Mutant Ninja Turtle	0.30%	468 msec
Mutant Ninja Turtle (W)	0.27%	468 msec
Terminator3	1.22%	508 msec
Wizard of OZ	0.40%	378 msec
Xanadu (Widescreen)	3.33%	428 msec

Table 7.8: Number of underflows with various buffering time for $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$

	300 msec	350 msec	400 msec	450 msec
3 Tenors in concert 1994	64	7	0	0
8mm	106	28	4	0
A.I. (Widescreen)	225	41	7	3
Baby's Day Out	860	217	36	8
Baby's Day out (W)	833	165	14	0
Beautiful Mind	268	60	11	1
Before Sunrise	32	2	0	0
Before Sunrise (W)	21	5	0	0
Cast Away	464	94	9	0
Dear Hunter	36	5	4	2
Hannibal	166	20	2	0
Last Samurai	36	4	0	0
Life is Beautiful	232	20	0	0
Lilo & Stitch	854	117	12	1
Lord of the Ring I	125	9	0	0
Lord of the Ring II	248	33	8	1
Lord of the Ring III	275	25	0	0
Lovers on the Bridge	123	29	2	0
Man in the Iron Mask	850	178	8	0
Matrix	70	8	4	0
Matrix Reloaded	41	6	0	0
Matrix Revolutions	43	8	1	0
Passport to Paris	79	13	2	0
Perfect Storm	7	0	0	0
Princess Caraboo	47	10	6	3
Queen	10	0	0	0
Runaway Bride	262	36	2	0
Saving Private Ryan	135	11	0	0
Scooby Doo	21	3	0	0
Shrek	212	38	3	0
Sound of Music	1227	274	40	1
Star Wars II	158	11	0	0
Mutant Ninja Turtle	18	5	2	0
Mutant Ninja Turtle (W)	16	5	2	0
Terminator3	116	30	9	4
Wizard of OZ	15	1	0	0
Xanadu (Widescreen)	128	17	1	0

CHAPTER 8
CONCLUSIONS AND FUTURE WORK

In this dissertation, the problems of multimedia video modeling and bandwidth reservation have been discussed. First, a two gamma function was used to model the multimedia video traffic, reducing the mean square errors while comparing the probability density function. Second, a bandwidth allocation scheme using a smoothing technique was applied to allocate the bandwidth efficiently. Prior knowledge of frame size is not required to calculate the required bandwidth. The smoothing technique can also reduce the burstiness and peak bandwidth requirements. The simulation results promise to resolve the issues previously mentioned above.

8.1 Multimedia Traffic Modeling

MPEG-2 traffic modeling with two gamma functions would be used as a traffic source for simulation, design, performance testing, and traffic control on the network.

The collection of 37 movies for the MPEG frame information was conducted. The frame type and size information for 37 different genres, running times, manufacture companies, and ratings is available for other researchers to contribute to traffic modeling and network development at http://www.list.ufl.edu/MPEGMoviesInfo. Previously, there was no such data for the MPEG related industry available.

MPEG traffic modeling of other papers uses the arithmetic mean and variance from the empirical frame size information. In this dissertation, a nonlinear least-square data fitting algorithm was used to calculate the gamma distribution modeling parameters. As shown in Table 6.2, it gives lower error percentage. Furthermore, it was extended to two gamma function distribution modeling. Two gamma function modeling has more flexibility to fit the curves.

The three gamma function modeling and higher was tested. The nonlinear least-square data fitting algorithm for the three gamma function modeling poses problems with calculation

complexities. It took a long time to fit more parameters than two gamma function modeling. Comparing the error results of three or more gamma function modeling with two gamma function modeling, the result was not always better than two.

Before completing the comparison for each movie frame size data, it was assumed that traffic characteristics vary depending on the movie genre. High action and drama movies are assumed to have different traffic properties. However the mean, variance, skewness, and kurtosis were compared, and the results show that there is no correlation between movie genre and frame size traffic properties.

The future work on this part would aim to reduce the calculation time to find the optimal parameters.

8.2 Traffic Prediction and Admission Control

MPEG-2 file format transmission through reservation, Call Admission Control, or a TDMA session could be performed by this bandwidth allocation scheme with optimal resource usage.

The proposed bandwidth assignment scheme does not need any prior frame information to estimate the required bandwidth. Other methods require prior frame information to calculate the required bandwidth or several seconds of buffering time. The presented bandwidth allocation scheme assigns the bandwidth dynamically and it needs 500 msec buffering time, using only the current buffer size information. In addition, this bandwidth allocation scheme can reduce wasted resources drastically without dropping any single frame, when compared to the minimum reservation method. Another advantage of this scheme is that it minimizes the calculation complexity to estimate the required bandwidth.

The extensive simulations to find the parameters from 37 movies frame data give $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$. The simulation result shows that there were no dropped frames and less than 10% bandwidth increment from the average data rate. There is a better combination of the parameters for each movie, which is shown in Table A.5. The best effort value can be used when the application permits changing the parameters because it yields improved delay time or reduced bandwidth assignment. These could be completed for the movie ahead of time. Here are several possible scenarios for DVD movie transmission.

(1) Best: Embedded prediction data into source stream as control, but it must be able to need this on the fly at bandwidth allocation level,

(2) Next best: Get best parameters for movie and put these in a control message at start. Push down to bandwidth allocation level as control message (e.g., VLAN tag data). But DVD manufacturers must do this at source, make control message, etc.,

(3) Pretty good: Use $\alpha = 0.94$, $\beta = 0.87$, and $\gamma = 10$ and expect nothing from DVD. No control message needed,

(4) Poor: Use existing schemes.

The transmit buffer and receiver buffer size for this system require 555KB for transmit side and 656KB for receiver side. Many home networking device manufacturers implemented the buffer size larger than 1 MB for supporting the future multimedia environment. The simulation result shows that less than 1 MB is needed for the MAC buffer of a network interface card to give good performance with a proposed scheme.

The future work on this part could be extended to adjust the parameters according to movie characteristics dynamically.

APPENDIX
Additional Tables

The Appendix will include several tables which help to understand this dissertation. Table A.1 and A.2 shows the required bandwidth and underflows with $\alpha = 0.92$, $\beta = 0.76$, and $\gamma = 15$. The assigned bandwidth changes the value according to the initial value of buffer size. Three initial bandwidth sizes, 2500, 5000, and 7500, were chosen to check the variation of buffer size and assigned bandwidth for this simulation. Table A.3 and A.4 shows the required buffer size and delay time with $\alpha = 0.92$, $\beta = 0.76$, and $\gamma = 15$. The same initial bandwidth were used in Table A.1 and A.2. Table A.5 shows the required bandwidth and delayed time with best effort. Each movie has different α, β, and γ values. The best parameter for each movie reduces the required bandwidth and delayed time. Table A.6 shows average and variance of the each frame. Table A.7 shows I vs.P frame, I vs.B frame, and P vs. B frame ratio.

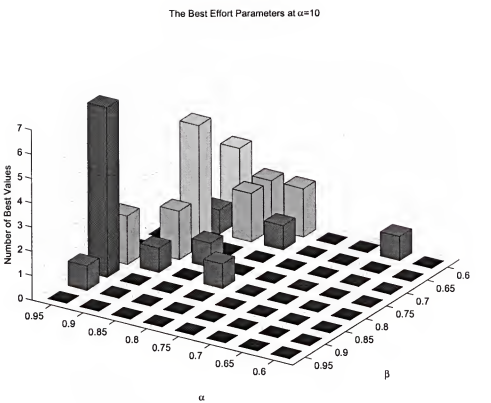

Figure A.1: Best effort parameters at $\gamma = 10$

Table A.1: Required bandwidth and underflows with $\alpha = 0.92$, $\beta = 0.76$, and $\gamma = 15$

	Initial BW	% of increased bandwidth	Assigned bandwidth (original)	Number of underflow
3 Tenors in concert	2500	0.75%	4.70Mbps(4.66Mbps)	0
	5000	1.69%	4.74Mbps	0
	7500	4.1%	4.85Mbps	0
8mm	2500	1.85%	4.63Mbps(4.55Mbps)	0
	5000	3.16%	4.69Mbps	0
	7500	5.94%	4.85Mbps	0
A.I. (Widescreen)	2500	1.31%	7.46Mbps(7.36Mbps)	2
	5000	2.10%	7.52Mbps	0
	7500	3.26%	7.60Mbps	0
Baby's Day Out	2500	9.18%	5.87Mbps(5.38Mbps)	2
	5000	12.26%	6.04Mbps	0
	7500	16.23%	6.25Mbps	0
Baby's Day Out (W)	2500	2.22%	5.52Mbps(5.40Mbps)	0
	5000	3.88%	5.61Mbps	0
	7500	6.76%	5.76Mbps	0
Beautiful Mind	2500	1.87%	7.29Mbps(7.16Mbps)	1
	5000	2.89%	7.37Mbps	0
	7500	4.37%	7.47Mbps	0
Before Sunrise	2500	0.41%	6.13Mbps(6.11Mbps)	0
	5000	0.78%	6.16Mbps	0
	7500	1.67%	6.21Mbps	0
Before Sunrise (W)	2500	0.43%	6.15Mbps(6.11Mbps)	0
	5000	0.81%	6.17Mbps	0
	7500	1.71%	6.23Mbps	0
Cast Away	2500	1.46%	7.40Mbps(7.30Mbps)	0
	5000	2.36%	7.46Mbps	0
	7500	3.73%	7.56Mbps	0
Deer Hunter	2500	1.15%	4.80Mbps	1
	5000	2.20%	4.85Mbps	0
	7500	4.25%	4.94Mbps	0
Hannibal	2500	1.08%	8.43Mbps(8.34Mbps)	0
	5000	1.75%	8.49Mbps	0
	7500	2.76%	8.57Mbps	0
Last Samurai	2500	0.27%	6.91Mbps(6.89Mbps)	0
	5000	0.44%	6.92Mbps	0
	7500	0.72%	6.94Mbps	0
Lilo & Stitch	2500	4.37%	6.68Mbps(6.34Mbps)	0
	5000	6.15%	6.79Mbps	0
	7500	8.62%	6.95	0
Life is Beautiful	2500	2.72%	7.20Mbps(7.01Mbps)	0
	5000	4.12%	7.30Mbps	0
	7500	5.99%	7.43Mbps	0
Lord of the Ring I	2500	4.4%	6.10Mbps(5.84Mbps)	0
	5000	6.34%	6.21Mbps	0
	7500	9.19%	6.38Mbps	0
Lord of the Ring II	2500	2.82%	6.07Mbps(5.90Mbps)	1
	5000	4.34%	6.16Mbps	0
	7500	6.62%	6.29Mbps	0
Lord of the Ring III	2500	3.62%	5.86Mbps(5.66Mbps)	0
	5000	5.02%	5.94Mbps	0
	7500	7.45%	6.08Mbps	0
Lovers on the Bridge	2500	1.57%	7.47Mbps(7.35Mbps)	0
	5000	2.44%	7.53Mbps	0
	7500	3.73%	7.62Mbps	0

Table A.2: Continued

	Initial BW	% of increased bandwidth	Assigned bandwidth (original)	Number of underflow
Matrix	2500	0.65%	5.40Mbps(5.37Mbps)	0
	5000	1.51	5.43	0
	7500	2.34	5.49	0
Matrix Reloaded	2500	0.34%	6.77Mbps(6.75Mbps)	0
	5000	0.60%	6.79Mbps	0
	7500	1.07%	6.82Mbps	0
Matrix Revolutions	2500	0.39%	6.62Mbps(6.59Mbps)	0
	5000	0.62%	6.63Mbps	0
	7500	1.04%	6.66Mbps	0
Passport to Paris	2500	0.71%	5.04Mbps(5.00Mbps)	0
	5000	1.33%	5.07Mbps	0
	7500	2.84%	5.15Mbps	0
Perfect Storm	2500	0.15%	7.28Mbps(7.27Mbps)	0
	5000	0.25%	7.29Mbps	0
	7500	0.42%	7.30Mbps	0
Princess Caraboo	2500	0.83%	5.99Mbps(5.95Mbps)	2
	5000	1.62%	6.04Mbps	1
	7500	3.10%	6.13Mbps	0
Queen	2500	1.55%	6.47Mbps(6.37Mbps)	0
	5000	2.52%	6.54Mbps	0
	7500	4.17%	6.64Mbps	0
Runaway Bride	2500	1.32%	8.56Mbps(8.45Mbps)	0
	5000	1.99%	8.62Mbps	0
	7500	2.93%	8.70Mbps	0
Saving Private Ryan	2500	0.95%	6.04Mbps(5.99Mbps)	0
	5000	1.69	6.08	0
	7500	3.00	6.16	0
Scooby Doo	2500	0.16%	7.74Mbps(7.73Mbps)	0
	5000	0.26%	7.75Mbps	0
	7500	0.43%	7.76Mbps	0
Shrek	2500	1.45%	8.71Mbps(8.59Mbps)	0
	5000	2.09	8.76	0
	7500	2.99	8.84	0
Sound of Music	2500	2.99%	6.61Mbps(6.42Mbps)	0
	5000	4.60%	6.71Mbps	0
	7500	6.91%	6.86Mbps	0
Star Wars II	2500	1.45%	7.14Mbps(7.04Mbps)	0
	5000	2.20%	7.19Mbps	0
	7500	3.39%	7.27Mbps	0
Mutant Ninja Turtle	2500	0.18%	6.20Mbps(6.19Mbps)	0
	5000	0.33%	6.21Mbps	0
	7500	0.67%	6.23Mbps	0
Mutant Ninja Turtle (W)	2500	0.18%	6.27Mbps(6.25Mbps)	0
	5000	0.0031%	6.27Mbps	0
	7500	0.60%	6.25Mbps	0
Terminator3	2500	0.68%	8.29Mbps(8.23Mbps)	2
	5000	1.17%	8.33Mbps	1
	7500	1.96%	8.39Mbps	0
Wizard of OZ	2500	0.34%	5.21Mbps(5.19Mbps)	0
	5000	0.59%	5.22Mbps	0
	7500	1.38%	5.26Mbps	0
Xanadu (Widescreen)	2500	2.51%	5.88Mbps(5.74Mbps)	0
	5000	4.04%	5.97Mbps	0
	7500	6.38%	6.10Mbps	0

Table A.3: Required buffer size and delay time with $\alpha = 0.92$, $\beta = 0.76$, and $\gamma = 15$

	Initial BW	Avg. Tx buffer size in KB(max)	Avg. Rx buffer size in KB(max)	Avg. delay time in msec(max)
3 Tenors in concert	2500	59(310)	208(417)	118(388)
	5000	49(290)	218(428)	99(363)
	7500	38(267)	229(438)	79(338)
8mm	2500	57(550)	203(503)	113(453)
	5000	48(540)	212(512)	97(428)
	7500	38(519)	223(524)	78(428)
A.I. (Widescreen)	2500	112(501)	311(555)	138(548)
	5000	99(471)	323(570)	123(438)
	7500	87(435)	336(583)	109(403)
Baby's Day Out	2500	64(521)	245(547)	103(523)
	5000	57(507)	251(556)	92(468)
	7500	51(481)	258(566)	81(443)
Baby's Day Out (W)	2500	76(427)	234(552)	125(488)
	5000	64(405)	246(566)	107(423)
	7500	53(382)	257(576)	89(398)
Beautiful Mind	2500	106(463)	305(587)	133(513)
	5000	94(449)	317(589)	119(438)
	7500	82(436)	328(599)	105(413)
Before Sunrise	2500	89(359)	261(442)	134(408)
	5000	76(346)	274(455)	117(348)
	7500	63(333)	287(468)	99(343)
Before Sunrise (W)	2500	89(383)	262(439)	134(433)
	5000	77(367)	275(367)	117(383)
	7500	64(359)	288(466)	99(373)
Cast Away	2500	111(538)	308(556)	138(473)
	5000	98(523)	321(558)	123(448)
	7500	86(486)	333(574)	108(423)
Deer Hunter	2500	54(284)	218(406)	108(523)
	5000	45(272)	227(415)	92(328)
	7500	37(262)	235(425)	77(303)
Hannibal	2500	128(713)	351(613)	139(463)
	5000	115(662)	364(615)	126(438)
	7500	102(612)	377(624)	114(413)
Last Samurai	2500	98(469)	297(491)	132(408)
	5000	86(430)	309(504)	117(373)
	7500	74(401)	322(516)	103(333)
Lilo & Stitch	2500	95(542)	272(539)	133(463)
	5000	85(514)	282(539)	118(413)
	7500	74(486)	293(540)	104(408)
Life is Beautiful	2500	94(377)	308(538)	122(463)
	5000	83(360)	319(543)	109(408)
	7500	74(344)	329(551)	97(368)
Lord of the Ring I	2500	69(536)	266(508)	106(403)
	5000	60(521)	275(518)	93(383)
	7500	52(501)	283(529)	81(378)
Lord of the Ring II	2500	82(523)	256(544)	123(513)
	5000	71(509)	267(557)	107(478)
	7500	61(488)	278(570)	92(448)
Lord of the Ring III	2500	76(543)	248(509)	119(423)
	5000	68(527)	257(515)	106(398)
	7500	58(502)	267(522)	91(378)
Lovers on the Bridge	2500	111(522)	311(544)	137(418)
	5000	99(501)	323(558)	123(393)
	7500	87(476)	335(560)	109(368)

Table A.4: Continued

	Initial BW	Avg. Tx buffer size in KB(max)	Avg. Rx buffer size in KB(max)	Avg. delay time in msec(max)
Matrix	2500	77(378)	231(412)	131(488)
	5000	64(362)	244(426)	111(413)
	7500	51(345)	257(440)	91(338)
Matrix Reloaded	2500	97(483)	290(544)	132(443)
	5000	85(449)	303(554)	117(403)
	7500	72(410)	315(563)	102(373)
Matrix Revolutions	2500	94(588)	284(511)	131(443)
	5000	82(550)	296(524)	116(413)
	7500	70(509)	309(530)	101(383)
Passport to Paris	2500	71(425)	216(369)	131(423)
	5000	58(403)	229(383)	109(398)
	7500	45(374)	242(396)	88(373)
Perfect Storm	2500	104(428)	313(503)	132(348)
	5000	91(412)	326(516)	118(338)
	7500	79(395)	338(529)	104(323)
Princess Caraboo	2500	86(444)	256(523)	130(568)
	5000	73(420)	268(536)	112(518)
	7500	61(395)	280(549)	95(443)
Queen	2500	94(412)	272(478)	129(383)
	5000	81(397)	285(492)	112(358)
	7500	69(377)	296(505)	96(323)
Runaway Bride	2500	130(488)	355(585)	140(428)
	5000	117(450)	368(585)	127(408)
	7500	105(424)	380(591)	115(383)
Saving Private Ryan	2500	87(482)	256(531)	131(433)
	5000	75(461)	269(540)	113(423)
	7500	62(433)	281(545)	96(408)
Scooby Doo	2500	112(420)	332(505)	134(453)
	5000	99(407)	344(521)	121(428)
	7500	87(387)	357(537)	107(403)
Shrek	2500	131(431)	362(616)	138(408)
	5000	118(417)	375(625)	126(393)
	7500	106(399)	387(634)	114(378)
Sound of Music	2500	97(539)	272(550)	134(478)
	5000	85(507)	284(551)	118(453)
	7500	74(475)	295(564)	103(428)
Star Wars II	2500	106(683)	297(541)	135(468)
	5000	93(647)	310(555)	120(443)
	7500	81(601)	323(569)	105(413)
Ninja Turtle	2500	90(323)	266(431)	134(468)
	5000	77(310)	278(444)	118(403)
	7500	64(296)	291(452)	100(323)
Ninja Turtle (W)	2500	90(337)	269(431)	134(473)
	5000	78(319)	281(443)	118(403)
	7500	65(304)	294(457)	101(348)
Terminator3	2500	122(577)	350(559)	136(533)
	5000	109(536)	363(569)	123(508)
	7500	97(485)	376(569)	110(468)
Wizard of OZ	2500	73(379)	225(440)	130(408)
	5000	60(357)	237(452)	111(383)
	7500	47(333)	250(466)	90(328)
Xanadu (W)	2500	84(592)	245(564)	129(408)
	5000	72(574)	257(577)	111(408)
	7500	61(554)	268(584)	94(383)

Table A.5: Required bandwidth with best effort

	% of increased bandwidth	Max delay time	α	β	γ
3 Tenors in concert 1994	4.14 %	318	0.90	0.70	10
8mm	0.60 %	428	0.85	0.75	10
A.I. (Widescreen)	0.75 %	498	0.80	0.60	10
Baby's Day Out	6.22 %	498	0.65	0.60	10
Baby's Day out (W)	3.36 %	443	0.90	0.80	10
Beautiful Mind	2.06 %	463	0.95	0.90	10
Before Sunrise	2.16 %	318	0.95	0.85	10
Before Sunrise (Widescreen)	0.46 %	383	0.85	0.65	10
Cast Away	6.52 %	388	0.95	0.85	10
Dear Hunter	0.01 %	483	0.80	0.80	10
Hannibal	6.32 %	368	0.95	0.85	10
Last Samurai	2.89 %	333	0.90	0.60	10
Life is Beautiful	6.40 %	388	0.85	0.65	10
Lilo & Stitch	3.98 %	463	0.80	0.60	10
Lord of the Ring I	6.16 %	363	0.80	0.65	10
Lord of the Ring II	5.51 %	438	0.85	0.60	10
Lord of the Ring III	5.77 %	383	0.90	0.75	10
Lovers on the Bridge	1.86 %	393	0.95	0.85	15
The Man in the Iron Mask	3.18 %	413	0.90	0.65	15
Matrix	5.59 %	413	0.95	0.80	10
Matrix Reloaded	1.17 %	363	0.90	0.70	10
Matrix Revolutions	0.28 %	403	0.80	0.60	10
Passport to Paris	2.81 %	378	0.95	0.85	10
Perfect Storm	1.34 %	303	0.90	0.65	10
Princess Caraboo	5.25 %	443	0.65	0.60	5
Queen	3.76 %	293	0.95	0.85	10
Runaway Bride	4.98 %	388	0.90	0.70	10
Saving Private Ryan	6.25 %	373	0.90	0.60	10
Scooby Doo	0.81 %	353	0.95	0.85	10
Shrek	5.25 %	378	0.90	0.70	10
Sound of Music	3.50 %	458	0.95	0.85	15
Star Wars II	3.82 %	363	0.90	0.70	10
Mutant Ninja Turtle	3.28 %	433	0.60	0.60	5
Mutant Ninja Turtle (W)	2.04 %	418	0.90	0.60	10
Terminator3	4.08 %	458	0.95	0.85	10
Wizard of OZ	4.01 %	298	0.95	0.80	10
Xanadu (Widescreen)	4.06 %	393	0.90	0.75	10

Table A.6: Average and variance of the each frame

	I Avg. (KB)	I Var (x 10^8)	P Avg. (KB)	P Var (x 10^8)	B Avg. (KB)	B var (x 10^8)
3 Tenors in concert	63.5	4.32	27.3	0.60	15.2	0.21
8mm	47.5	3.92	28.2	1.12	17.5	0.30
A.I. (W)	86.3	10.10	43.5	2.68	28.1	2.70
Baby's Day Out	102.2	6.84	26.0	2.22	16.4	0.55
Baby's Day out (W)	79.0	3.29	31.1	1.66	17.9	0.34
Beautiful Mind	106.4	15.21	41.0	3.43	25.0	1.42
Before Sunrise	74.6	2.25	41.0	1.24	21.1	0.38
Before Sunrise (W)	74.8	2.39	41.3	1.23	21.0	0.40
Cast Away	119.4	10.88	34.5	1.38	25.7	0.59
Dear Hunter	55.3	1.01	24.9	0.45	19.7	0.20
Hannibal	143.2	10.62	37.8	1.17	29.3	0.49
Last Samurai	60.0	2.27	42.6	0.77	28.2	0.40
Life is Beautiful	122.3	7.10	32.2	1.44	24.4	0.51
Lilo & Stitch	119.6	11.49	27.6	1.75	21.2	1.81
Lord of the Ring I	77.8	4.20	35.3	2.58	20.8	0.99
Lord of the Ring II	72.2	7.40	39.6	2.78	20.3	1.00
Lord of the Ring III	70.9	3.86	35.4	2.54	20.2	1.09
Lovers on the Bridge	125.8	8.33	43.8	2.65	23.0	0.61
Man in the Iron Mask	64.5	2.00	28.3	1.13	15.9	0.28
Matrix	58.1	1.02	34.3	0.78	20.1	0.30
Matrix Reloaded	61.4	3.75	43.0	1.02	26.7	0.39
Matrix Revolutions	53.9	1.97	41.3	0.62	27.2	0.52
Passport to Paris	54.9	1.61	37.1	1.17	17.2	0.23
Perfect Storm	54.9	2.15	47.0	0.71	30.0	0.56
Princess Caraboo	72.1	5.54	36.5	1.67	21.9	0.38
Queen	66.7	3.26	44.6	1.81	22.7	0.91
Runaway Bride	133.8	5.90	37.8	1.85	31.5	0.62
Saving Private Ryan	64.8	3.54	39.4	1.51	21.7	0.58
Scooby Doo	67.0	2.20	47.7	0.98	31.7	0.37
Shrek	139.5	12.22	57.0	5.98	25.6	0.95
Sound of Music	120.2	5.54	29.7	1.63	21.3	0.58
Star Wars II	92.7	4.77	36.9	1.80	26.5	0.80
Mutant Ninja Turtle	55.8	1.45	37.1	0.61	25.5	0.25
Mutant Ninja Turtle (W)	56.2	1.44	36.8	0.56	26.1	0.27
Terminator3	116.9	12.55	50.5	3.10	28.1	0.50
Wizard of OZ	58.6	1.63	36.0	0.99	18.1	0.17
Xanadu (Widescreen)	76.0	8.94	36.9	2.51	19.5	0.90

Table A.7: I vs.P frame, I vs.B frame, and P vs. B frame ratio

	$\frac{I}{P}$ Frame ratio	$\frac{I}{B}$ Frame ratio	$\frac{B}{P}$ Frame ratio
3 Tenors in concert	2.32	4.17	1.79
8mm	1.68	2.71	1.61
A.I. (W)	1.98	3.07	1.54
Baby's Day Out	3.93	6.23	1.58
Baby's Day out (W)	2.54	4.41	1.73
Beautiful Mind	2.59	4.25	1.64
Before Sunrise	1.81	3.53	1.94
Before Sunrise (W)	1.81	3.56	1.96
Cast Away	3.46	4.64	1.34
Dear Hunter	2.22	2.80	1.26
Hannibal	3.78	4.88	1.29
Last Samurai	3.79	5.01	1.31
Life is Beautiful	4.33	5.64	1.30
Lilo & Stitch	1.40	2.12	1.51
Lord of the Ring I	2.20	3.74	1.69
Lord of the Ring II	1.82	3.55	1.95
Lord of the Ring III	2.00	3.50	1.75
Lovers on the Bridge	2.87	5.46	1.90
Man in the Iron Mask	2.27	4.05	1.77
Matrix	1.69	2.89	1.70
Matrix Reloaded	1.42	2.29	1.61
Matrix Revolutions	1.30	1.98	1.51
Passport to Paris	1.47	3.19	2.15
Perfect Storm	1.16	1.83	1.56
Princess Caraboo	1.97	3.29	1.66
Queen	1.49	2.93	1.96
Runaway Bride	3.53	4.24	1.20
Saving Private Ryan	1.64	2.98	1.81
Scooby Doo	1.40	2.11	1.50
Shrek	2.44	5.44	2.22
Sound of Music	4.04	5.64	1.39
Star Wars II	2.51	3.49	1.39
Mutant Ninja Turtle	1.50	2.18	1.45
Mutant Ninja Turtle (W)	1.52	2.15	1.40
Terminator3	2.31	4.16	1.79
Wizard of OZ	1.62	3.23	1.98
Xanadu (Widescreen)	2.05	3.89	1.89

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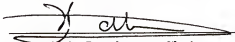

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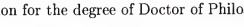

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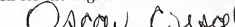

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